University of Alberta

Satellite Characterization of Vegetation Dynamics in the Western Canadian Boreal Plain

by

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ABSTRACT

A total of 10 per-pixel Vegetation Phenological Metrics (VPMs) were developed to investigate the spatial and inter-annual phenological trends of 16 watersheds using 4 year time-series satellite Vegetation Index (VI) data. The VPMs, derived from the Enhanced Vegetation Index (EVI), coincided well with ground phenological observations and hence, were concluded to be realistic. The end of the growing season metric appeared to be a more sensitive indicator of the watershed health than the beginning; the longer growing season appeared to be a function of a delayed end rather than an early beginning, while industrial activities had a length shortening effect. Temperature is the major driver of the vegetation dynamics, especially in the wet years, with biomass accumulation being a function of Growing Degree Days (GDD) and moisture availability. The results, while initial, are encouraging and provide information about the physiological rather than the structural condition of the watersheds.

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List of Abbreviations

ANOVA	Analysis of Variance
AOI	Area of Interest
AOT	Aerosol optical thickness
ARMA	Auto Regressive Moving Average
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
AVI	Alberta Vegetation Inventory
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BB	Blackbody
BIL	Binary Interleaved
BISE	Best Index Slope Extraction
BOREAS	Boreal Ecosystem-Atmosphere Study
BRDF	Bi-directional Reflectance Distribution Function
CV-MVC	Constrained View Maximum Value Composite
DC	Digital Count
DEM	Digital elevation model
DFMP	Detailed Forest Management Plan
DN	Digital Number
DTAC	Dark target-based atmospheric correction
EG	End of greenup
EOS	Earth Observing System
EOSDIS	Earth Observing System Data Information System
ESE	Earth System Enterprise
EVI	Enhanced Vegetation Index
fAPAR	fraction of absorbed photosynthetically active radiation
FMA	Forest Management Agreement
FMPM	Forest Management Planning Manual
FORWARD	Forest Watershed and Riparian Disturbance
ftp	File transfer protocol
GCP	Ground control point
GDD	Growing Degree Days
GIS	Geographic Information Systems
GMT	Greenwich Mean Time
HDF	Hierarchal Data Format
IMAR	Inner Mongolia Autonomous Region
L1B	Level 1B
L3	Level 3
LAI	leaf area index
Landsat	Land Satellite

LP DAAC	Land Processes Distributed Active Archive Center
LST	Land surface temperature
LULC	Land use land cover
MAS	MODIS Airborne Simulator
MAST	MODIS Administrative Support Team
MCST	MODIS Characterization Support Team
MCT	Multiple Comparison Test
MLST	MODIS Land Science Team
MODAPS	MODIS Data Processing System
MODIS	Moderate Resolution Imaging Spectroradiometer
MODLAND	MODIS Land
MODLAND	MODIS Land
MQUALS	MODLAND Quick Airborne Looks
MS DOS	Microsoft Disk Operating System
MSS	Multispectral Scanning Spectrometer
MT	Mean Temperature
MVC	Maximum Value Composite
NASA	National Aeronautics and Space Administration
NBAR	Nadir bidirectional reflectance distribution function adjusted reflectance
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NIR	Near Infra Red
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Production
NRDC	National Resources Defense Council
OBC	On-Board Calibrator
OFRI	Ontario Forest Research Institute
OG	Onset of greenup
OGR	Operating ground rule
OGS	Onset of greenness/greenup and senescence
PGE	Product Generation Executive
PVL	Parameter Value Language
QA	Quality Assurance
REMAP	Regional Environmental Monitoring and Assessment Program
RMS	Root mean square
RS	Remotely sensed
SD	Solar Diffuser
SDSM	Solar Diffuser Stability Monitor
SRCA	Spectroradiometric Calibration Assembly
TM	Thematic Mapper
TOA	Top-of-atmosphere
TP	Total Precipitation
TR	Total Rain
TS	Total Snow
U.S. EPA	United States Environmental Protection Agency

USDA	United States Department of Agriculture
VI	Vegetation Index
VPM	Vegetation phenological metric
WQ	Water Quality

Chapter 1

Introduction

1.1 Sustainable Forest Management

Forests cannot be managed wisely and efficiently in isolation without taking into account the larger landscape in which individual stands occur (Sachs et al. 1998). Considerable uncertainty exists, however, as to how natural and anthropogenic disturbances and management actions interact to determine landscape patterns and consequently how this interaction implicates sustainable resource management in terms of overall forest health preservation. Moreover, the current knowledge base falls short of predicting the effects of multiple land uses in catchment areas that overlap in time and space.

Poor forest management can have serious long-term consequences. For instance, management actions such as harvesting can alter landscape patterns (Franklin and Forman 1987; Ripple et al. 1991; Spies et al 1994) which in turn can impact biodiversity (Harris 1984, Lehmkuhl et al. 1991). Furthermore, management implications are crucial to water quality (Griffith 2002), regional climate and hydrology (Jones and Grant 1996), carbon budget (Dixon et al. 1994; Cohen et al. 1996), and global climate change (Schwartz 1999).

The above concerns have evolved into the conception of sustainable forest management, "the condition in which forest ecosystems sustain their complexity, diversity, resiliency, and productivity while providing for present and future human needs and values" (United States Department of Agriculture (USDA) Forest Service 2003). Sustainable resource management places considerable emphasis on maintaining forest ecosystem health, which is "the condition where a forest has the capacity across the landscape for renewal, for recovery from a wide range of disturbances, and for retention

of its ecological resiliency, while meeting current and future human needs for desired level of values, uses, products and services" (USDA Forest Service 2004).

1.2 Background

The Canadian Boreal forests, like the Amazon forests, are of global importance to all living beings on earth. The thick layers of moss, soil and peat of the Boreal region are the world's largest terrestrial storehouse of organic carbon and play an important role in regulating global climate change (Natural Resources Defense Council (NRDC) 2002). Boreal forests comprise approximately 77% of the forested land in Canada and cover 60% of the land area in Alberta (Alberta Sustainable Resource Development 2001*a*).

In 2002, Canadian forestry export value was $42.9 billion, making Canada the world's largest forest product exporter with 18% of trade in international forest products (Natural Resources Canada 2003*a*). The industry employs 361,400 Canadians and acts as a backdrop for a tourism industry that is worth several billion dollars annually (Natural Resources Canada 2003*a*). Furthermore, in 2001, Canada produced 803 million barrels of oil and 6.5 trillion cubic feet of gas, making it the world's 14th largest oil producer and 3rd largest gas producer (Price and Bennett 2002). A report released by Greenpeace, ForestEthics and the NRDC show that since 1975, logging companies have cut 25 million hectares of Canadian Boreal forest; the amount of land clearcut has increased by 40% in the last 28 years, posing a significant threat to biodiversity conservation: 431 species are listed as at risk on Canada's federal endangered species' list in addition to those listed provincially (Greenpeace Canada 2003). Moreover, the oil and gas activities have led to 20% increase in greenhouse gas emissions from 612 to 726 million metric tones, from 1990 to 2000 (Price and Bennett 2002).

In Alberta, the scale of these industries is magnified; a major forestry trend is the intensification of harvesting practices (Natural Resources Canada 2003*b*). Forest harvest activities have increased in Alberta from 21.9 million m^3 in 2000 (Natural Resources Canada 2002) compared to 6.5 million m^3 in 1984 (McDougall 1986) with less than 9% of Alberta's Boreal forest left intact (NRDC 2002). In addition, Alberta is the home to most of the Canadian oil and gas supply that since 1990 have increased by 47% and 69%, respectively (Price and Bennett 2002). The energy industry harvests and accesses, on

average, the same amount of land base as the forest industry (Smith et al. 2003*b*). While Alberta already has more than 150,000 kilometers of oil and gas roads slicing through the forest, to meet the growing demands, it is anticipated that 200,000 more gas wells would have to be drilled in Alberta, British Columbia, the Yukon, and the Northwest Territories within the next decade (Price and Bennett 2002).

The effects of this increased logging and oil and gas exploitation, as well as hydropower development, mining, road construction and other industrial activities in Alberta's Boreal ecosystem have led to a call from civil society for sustainable forest management practices. In order for industry and government to respond, tools are required that are verifiable and easy to use (Smith et al. 2003*b*) for the assessment and prediction of management impacts, to identify the biological and ecological system constraints for forest renewal, to investigate ecosystem response to stress, and to develop a clear picture of emerging and evolving problems in the wake of climate change issues.

Figure 1-1: Example of the Boreal plain landscape fragmentation in Swan Hills Alberta.

1.3 Alberta's Current Forest Management Infrastructure

Alberta's forest resources are managed through Forest Management Agreements (FMAs), which are area-based tenure agreement between a forest company and the Government of Alberta (Alberta Sustainable Resource Development 2004). It provides the forest company with the right to grow, harvest and remove timber (Alberta Sustainable Resource Development 2004). The terms of the FMA require forest product companies to assume full responsibility for the planning and sustainable management of forest resources within a designated area, and to produce a Detailed Forest Management Plan (DFMP) within every 10 years. FMA holders must use their own resources to obtain and distribute management and research information to stake holders including Government, quota holders, and the public. The DFMP reflects a company's strategy to manage timber on a long-term sustained yield basis and to effectively deal with forest health issues taking into account social, recreational, economic, biological and utilitarian aspects. The Government of Alberta prepares a Forest Management Planning Manual (FMPM) to direct how a DFMP within an FMA is to be written and approves the company's DFMP if it is written in accordance with the FMPM. The FMPM establishes the company's DFMP production schedule, lower level plan production and operating ground rules (OGR) construction (Smith et al. 2003*b*). Renewal of the FMA after 20 years is based on company performance and compliance with federal and provincial environmental regulation and policies (Alberta Sustainable Resource Development 2001*b*).

Smith et al. (2003*b*) and the Government of Alberta Sustainable Resource Development website at http://www3.gov.ab.ca/srd.html both provide a detailed insight into the interaction of the provincial government with forest product companies in managing the forested land base of Alberta.

1.4 Forest Watershed and Riparian Disturbance (FORWARD)

To date there is no formal process for integrating and assessing the cumulative impacts of industrial activities or other disparate overlapping human activities in Alberta's Boreal forests (Smith et al. 2003*b*). Recent provincial initiatives to develop policies and procedures to resolve these issues by moving from a focus on perpetual

sustained yield to a holistic sustainable management approach have encouraged forest companies to operate within a fairly broad spectrum of management. Without comprehensive tools or sufficient base data to develop operating field procedures though, the need to monitor, model and research ecosystem dynamics has become indispensable. It was in this industrial context that the Forest Watershed and Riparian Disturbance (FORWARD) project was conceived.

Members of academia, industry, and regulatory agencies are working together in FORWARD to monitor 16 natural and disturbed test watersheds on the Western Boreal Plain ecozone of the Canadian Boreal forest in the Swan Hills of Alberta. FORWARD in particular is focused on determining the influence of wildfire and harvest disturbances on nutrient (phosphorus and nitrogen) release to fresh waters leading to marine pollution. Using state-of-the-art instrumentation, data on vegetation, soils, surface water quality and quantity, and bioindicators have been collected on treatment versus reference and before versus after disturbance on small watershed streams in order to generate the long-term database necessary to simulate distributed deterministic and probabilistic models. Model outcomes are to be linked into decision support tools, specifically Millar Western Forest Products' DFMP, and will be applied to planning and management practices (Smith et al. 2003*a*)

Building on previous sustainability initiatives in Alberta such as Terrestrial and Riparian Organisms, Lakes and Streams (TROLS), Sustainable Forest Management Network (SFMN) and Northern River Basins Study (NRBS) (Alberta Environment 2002), FORWARD offers linkages with other Canadian long-term small stream forested projects such as the University of British Columbia Malcolm Knapp Experimental Research Forest, Canadian Forest Service Turkey Lakes Watershed and the Legacy Experimental Forest.

Detailed background to FORWARD is published in nine peer-reviewed papers in a special issue of the Journal of Environmental Engineering and Science. The project website can also be accessed at http://forward.lakeheadu.ca.html.

1.5 Research Objectives

Management at the regional level requires data about large areas. Moreover, this data must be consistent and comprehensive enough to establish its statistical power of significance. Only remote sensing can provide such data over an entire area rather than providing a sampling of it, as would be the case with ground based measurements.

In addition, the detection and monitoring of major phenological transition dates are crucial to understanding the cumulative, large-scale effects of past and future forest management decisions. Many studies have shown that environmental factors are closely related to plant development and growth but the ability to predict environmental control of vegetation phenology remains inadequate. Surface-atmosphere interactions involve complex feedbacks (Moulin et al. 1997) since surface vegetation responds actively to climate variability. The vegetation response to climate variation requires a thorough understanding of vegetation phenological cycles and their relationship to temperature and precipitation (Zhang et al. 2004).

In this study, a suite of Vegetation Phenological Metrics (VPMs), using 4 year time-series satellite vegetation data, was developed to describe the phenological phenomena of 16 test watersheds in the FORWARD study area. The 4 year inter-annual variability of these metrics in 16 watersheds was also investigated to identify the most consistent phenological characteristics of these watersheds.

The main objectives of this research are to:

1. assess the validity of the Vegetation Phenological Metrics (VPMs);
2. characterize the temporal and spatial dynamics of vegetation in 16 FORWARD watersheds;
3. investigate the relationship between the vegetation phenological events and climatic conditions; and
4. assess the environmental control of vegetation phenology.

1.6 Research Questions

In order to fulfill these objectives, this study attempts to answer the following questions:

1. How do VPMs derived from Zhang method compare with those derived from Zhang modified method?
2. How do VPMs derived from Normalized Difference Vegetation Index (NDVI) compare with those derived from Enhanced Vegetation Index (EVI) in achieving above objectives?
3. Does high time-integrated Vegetation Index (VI) (biomass accumulation) correspond to the availability of more heat over the same year?

1.7 Research Approach

A forest manager's wish list includes answers to questions such as how large an area can be harvested at one time or with 2 or 5 years difference to achieve sustainable practices. What are the guidelines for road construction near a stream? what are the maximum disturbance levels for harvesting, regenerating and thinning a stand? what are the operating ground rules? how to do harvest allocation and determine the shape of a harvest plot? how does one develop spatial guidance patterns? what are the vegetation patterns to be developed in the course of time? what are sustainable management actions with respect to wildlife habitat, biodiversity conservation, water supply quality, climate change, air quality, soil preservation, ecological integrity and aquatic populations (Russell 2004, verbal communication)?

Ecosystem resource management implies a broad and fuzzy concept that has to be treated within the context of defined strategies, goals and objectives (More 1996). While this research does not attempt to provide an answer to each of these questions individually, it does adopt a holistic and interdisciplinary approach to develop tools that has the potential to deal with these issues at the ecosystem and watershed level of organization. Specifically, this research investigates the potential of satellite derived vegetation phenology as an effective indicator of sustainability and a reliable tool that can be applied to understand ecosystem functioning. Research conclusions may be useful in

assessing ecosystem productivity at a regional scale (Duchemin et al. 1999), better accounting for forested ecosystems in modeling water and nutrient budgets, and quantifying the impact of climate variability on vegetation dynamics.

Chapter 2

Literature Review-I

Two areas of research are relevant to the research presented in this thesis: Remote sensing and the vegetation phenology. This chapter reports the literature dealing with the important aspects of remote sensing for assessing the vegetation condition. The review focuses on the remote sensing platform, and the theoretical background of vegetation indices used in this study. Concepts of image calibration, compositing, pre-processing, quality assurance and validation are also discussed.

2.1 Remote Sensing in Vegetation Studies

Remote sensing allows a scientist to gather information from a distance without coming into direct contact with the object or phenomenon of interest. While providing a systematic, synoptic view of the earth's cover over a wide range of spatial scales with repeated temporal sampling, it is a relatively cheap and easy-to-manipulate method of acquiring near-real time landscape data. Particularly, at larger scales, it is almost impossible to obtain consistent field observations to monitor vegetation conditions across different land covers which would represent ecosystem-level activity rather than species specific dynamics (White et al. 1997). In the last decade, various ecosystem models of evapotranspiration, photosynthesis and foliar nutrient cycling have been developed that require remotely sensed inputs such as Normalized Difference Vegetation Index (NDVI), leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (fAPAR).

2.1.1 The reflectance characteristics of vegetation

When sunlight strikes the earth's atmosphere and terrain features, each form of matter on earth transmits, absorbs, scatters or reflects solar radiation in a particular and characteristic manner. Chlorophyll in vegetation absorbs solar radiation primarily in the blue and red wavelengths to carry on photosynthetic activities, allowing green light to be

transmitted through and reflected from the leaves. Leaf cell structure also scatters and strongly reflects non-visible near infra-red (NIR) radiation to avoid over-heating. This characteristic spectral response signature, as shown in Figure 2-1, can be used to distinguish plants from non-living features on the earth's surface provided that we measure the reflected sunlight from earth features. This was made possible with the advent of photographic (light-sensitive copper plates, photographic films) and non-photographic sensors (photodiodes, photoconductors and charged-coupled devices) sampling within narrow wave bands of electro-magnetic radiation (Norwood and Lansing 1983). Reflected long wave radiation measured by these remote sensing sensors manifests itself as digital numbers (DNs) in each pixel of an image and contains information about plant canopy structure and function. The recorded radiation then needs to be calibrated against reality, however.

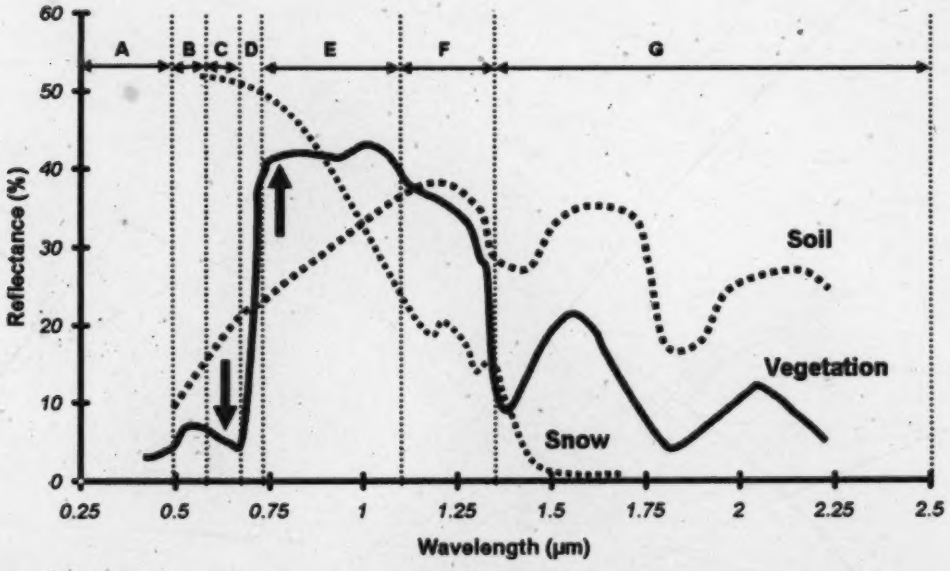

Figure 2-1: Spectral reflectance curve of a typical active vegetation with a generic soil and snow signature to show contrast. Region A: Chlorophyll blue light absorption, Region B: Green peak reflectance, Region C: Chlorophyll red light absorption, Region D: Transition, Region E: NIR plateau (strong reflectance): Region F: Transition, Region G: Leaf water absorption (developed from Tucker and Sellers 1986; Dozier and Frew 1981).

2.1.2 Vegetation Indices (VIs)

Vegetation Indices (VIs) are dimensionless, reflectance-based measurements computed from a combination of several spectral values that are added, divided or multiplied in a manner designed to yield a single value that indicates the amount or vigor of vegetation within the pixel. High values of VIs represent pixels covered by a significant proportion of healthy vegetation. VIs are used for their simplicity and relationship (either theoretical or empirical) to biophysical parameters (Asner et al. 2003). VI algorithms are designed to extract the vegetation signal portion from the measured reflected radiation by the sensor.

In general, VIs have been used to study watershed hydrologic processes, anthropogenic and climate change detection and modeling, agricultural activities (plant stress, insect attack, harvest yields), famine and drought early warning systems, landscape disturbances (volcanic, fire scars etc.), land use and land cover change, biophysical estimates of vegetation parameters (percent cover, fAPAR, LAI) and public health issues (Huete et al. 1999).

2.2 NASA's Earth Science Enterprise (ESE)

U.S. National Aeronautics and Space Administration (NASA) have several moderate and coarse spatial resolution sensing systems in orbit, scanning the whole earth's surface and collecting data. Earth Science Enterprise (ESE) is NASA's comprehensive program to study the earth as a complete environmental system. The overall objective of the ESE program is to determine how the earth is changing and the consequences for life on earth (Justice et al. 2002). Detailed background about the ESE program can be found at the NASA's website http://earth.nasa.gov/Introduction/index .html.

The Earth Observing System (EOS) is the key initiative of the ESE program. The EOS program, since its creation in 1958, has been focused on understanding the planet earth's air, land, water, and life as an integrated system, generating an extensive long-term database of remotely sensed observations. Key areas of study include clouds; water and energy cycles; oceans; chemistry of the atmosphere; land surface; water and ecosystem processes; glaciers and polar ice sheets; and the solid earth (NASA EOS

2004). EOS includes a series of satellites, a science component, and a data system which supports a coordinated series of polar-orbiting and low-inclination satellites (NASA EOS 2004).

2.2.1 Moderate Resolution Imaging Spectroradiometer (MODIS)

MODIS (or Moderate Resolution Imaging Spectroradiometer) is the key sensor on board NASA's Terra and Aqua satellites, which are part of the EOS satellite constellation, launched from Vandenberg Air Force Base, CA (MODIS Administrative Support Team (MAST) 2004). Terra was launched on December 18 1999 and began collecting data on February 24 2000. AQUA was launched on May 4 2002 and began collecting data on June 24 2002. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon (MAST 2004). Aqua's afternoon observations, combined with Terra's morning observations, provide important insight into the daily cycling of key environmental parameters such as precipitation and ocean circulation. Terra flies in formation with Landsat 7, which is another EOS satellite with a 30 m resolution sensor, providing a multi-scale sampling system for land surface monitoring (Justice et al. 1998).

MODIS' design is built on National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) and Landsat Thematic Mapper (TM) experience, to provide improved monitoring for land, ocean and atmospheric research. It has the highest number of spectral bands of any global coverage moderate resolution spectroradiometer. The land imaging component of this sensor has been upgraded by adding spectral bands in the middle and long-wave infrared (IR) and providing spatial resolution of 250 m and 500 m in addition to 1 km. The improved spectral resolution provides for better cloud and atmospheric characterization (Justice et al. 1998).

MODIS is viewing the entire earth's surface every 1 to 2 days, acquiring data in 36 spectral bands (MAST 2004). Table 2-1 provides technical specifications of MODIS sensor. Detailed specifications can be found at NASA's MODIS website http://modis.gsfc.nasa.gov/about/specs.html.

Table 2-1: MODIS' technical specifications (MAST 2004).

Parameters	Specifications
Orbit	705 km, 10:30 a.m. descending node (Terra) or 1:30 p.m. ascending node (Aqua), sun-synchronous, near-polar, circular, inclination 98.2°, mean period 98.9 min, 16 day repeat cycle
Scan Rate	20.3 rpm, cross track (Whisk broom)
Swath Dimensions	2330 km (cross track) by 10 km (along track at nadir)
Field of view	110°
Telescope	177.8 mm diam. off-axis, afocal (collimated), with intermediate field stop
Size	1.0 x 1.6 x 1.0 m
Weight	228.7 kg
Power	162.5 W (single orbit average)
Data Rate	10.6 Mbps (peak daytime); 6.1 Mbps (orbital average)
Quantization	12 bits
Daily coverage	30° latitude
Spatial resolution	250 m (bands 1 to 2), 500 m (bands 3 to 7), 1000 m (bands 8 to 36)
Design Life	6 years

2.2.2 MODIS Normalized Difference Vegetation Index (NDVI)

NDVI is a radiometric measure of vegetation that exploits the unique spectral signatures and behavior of canopy elements in the red and NIR portions of the spectrum (Asner et al. 2003). The two black arrows in Figure 2-1 indicate these unique spectral response regions. Deering (1978) came up with the normalized transform of the simple NIR to red reflectance ratio index, X_{NIR} / X_{red} (Jordan 1969), designed to standardize VI values to between -1 and +1 (Huete et al. 1999). The equation takes the form:

$$NDVI = \frac{\lambda_{NIR} - \lambda_{red}}{\lambda_{NIR} + \lambda_{red}} \quad [1]$$

Where;

λ = atmospherically corrected surface reflectances.

Rationing enables the NDVI to minimize calibration and instrument errors as well as changing reflectance conditions related to variable sun angles, cloud/shadow, aerosol content, atmospheric conditions and surface topography (Huete et al. 1999). High positive values of NDVI correspond to dense vegetation cover that is actively growing, where negative values are usually associated with bare soil, snow, clouds or non-vegetated surfaces.

NDVI derived from different sensors has been used by the research community in the last two decades and has been shown to correlate with several biophysical parameters such as chlorophyll density (Tucker et al. 1985), absorbed photosynthetically active radiation (Myneni and Williams 1994; Baret and Guyot 1991), LAI (Spanner et al. 1990; Asrar et al. 1984), productivity (Prince et al. 1995; Running 1990) and percent canopy cover (Yoder and Waring 1994). Relationships between fAPAR and NDVI have been shown to be near linear (Pinter 1993; Begué 1993; Wiegand et al. 1991). Other studies have shown the NDVI to be related to carbon-fixation (Raich and Schlesinger 1992; Fung et al. 1987), canopy resistance, and potential evapotranspiration (Running et al. 1989) allowing its use as input to models of biogeochemical cycles (Asrar et al. 1984).

MODIS NDVI is designed to serve as a "continuity index" to the existing NOAA-AVHRR 20-year global NDVI data set to provide for long-term vegetation monitoring studies. Huete et al. (1988) identified following disadvantages with the use of NDVI:

- an inherent non-linearity of ratio-based indices;
- the influence of additive noise effects (e.g. atmospheric path radiances);
- scaling problems;
- saturated signals over high biomass conditions; and
- sensitive to canopy background variations (strong NDVI degradation particularly, in higher canopy background brightness).

Because of NASA's EOS operational external noise removal, it was made possible to take advantage of non-ratio based indices (Huete et al. 2002) which are more linear

with less saturation problems (Richardson and Wiegand 1977). This allowed for the introduction of alternative VIs for vegetation monitoring.

2.2.3 MODIS Enhanced Vegetation Index (EVI)

The EVI is MODIS-specific and provides improved sensitivity in high biomass regions. It was developed to enhance vegetation monitoring capability through a de-coupling of the canopy background signal and a reduction in atmospheric influences (Huete et al. 2002). It will, however, take time to be fully evaluated in terms of its applicability and limitations before being fully adopted by the researching community (Huete et al. 2002). In contrast to the NDVI algorithm, EVI utilizes the more atmosphere-sensitive blue band to correct the red band for aerosol influence (Kaufman and Tanre' 1992). The equation takes the form:

$$\mathrm{EVI} = G\frac{\lambda_{NIR} - \lambda_{red}}{\lambda_{NIR} + C_1 \times \lambda_{red} - C_2 \times \lambda_{blue} + L} \qquad [2]$$

Where;

λ = atmospherically corrected or partially atmospherically corrected (Rayleigh and ozone absorption) surface reflectances

L = canopy background adjustment (to correct for non-linear, differential NIR and red radiant transfer through a canopy)

C1, C2 = coefficients of the aerosol resistance term

G = gain factor.

Currently, the coefficients in the EVI algorithm are set to $L = 1$, $C_1 = 6$, $C_2 = 7.5$, and $G = 2.5$ (Huete et al. 1994; Huete et al. 1997).

The EVI algorithm makes use of a sophisticated compositing scheme which reduces angular, sun-canopy-sensor variations using the Constrained View Maximum Value Composite (CV-MVC) and with an option to use a Bi-directional Reflectance Distribution Function (BRDF) Model (Huete et al. 2002). Moreover, EVI is sensitive to canopy structural variations, including LAI, canopy type, plant physiognomy, and canopy architecture (Gao et al. 2000) whereas NDVI is more responsive to chlorophyll.

2.3 Remote Sensing Data Quality Considerations

MODIS VI data quality assessment includes calibration, image pre-processing, compositing, quality assurance (QA), and validation.

2.3.1 Calibration

Instrument calibration is the key to developing a stable time-series database. Pre-launch MODIS instrument characterization included radiometric, spectral, spatial, and polarization sensitivity analysis. On-Board Calibrators (OBCs); the Blackbody (BB), Solar Diffuser (SD), Solar Diffuser Stability Monitor (SDSM), and the Spectroradiometric Calibration Assembly (SRCA) generate various stimuli to monitor change in pre-launch characteristics and to establish post-launch absolute calibration in reflectance units in the reflective bands and in radiance units in the thermal bands (Guenther et al. 2002).

MODIS multiple calibration systems provide on-orbit calibration and ensure 2% calibration accuracy relative to the sun's radiance (Guenther et al. 2002). MODIS vicarious calibrations use high-altitude clouds and ocean observations to first perform the band to band registration and then the absolute calibration of the visible bands (Justice et al. 1998). Additional external calibration sources look at the moon and deep space. Looking at the moon provides for tracking degradation of the SD, while looking at deep space provides a photon input signal of zero, (stars are too dim to be "seen" by MODIS) which is used as an additional point of reference for calibration (MODIS Characterization Support Team (MCST) 2003). Detailed MODIS instrument geometry and calibration insight is provided by MCST (2003).

2.3.2 Image pre-processing

At-sensor recorded radiations from the terrain is a complex and composite function of the characteristics of the instrument; the size, shape, color, orientation, chemical composition and water content of plant, soils, water bodies; the density, distribution and juxtaposition of terrain features within landscape; and the noise introduced by the intervening atmosphere (Wilkie and Finn 1996). There is a history of VI research identifying limitations, which may impact upon VI utility in change detection, vegetation monitoring or biophysical parameter estimation studies. External influences and inherent

variations to vegetation canopies (such as canopy structural effects associated with leaf angle distribution, clumping and non-photosynthetically active components) affect the VI values and hence must be accounted for before deriving any meaningful conclusions.

RS VI imagery artifacts can be introduced by many sometimes interrelated (overlapping), sources which include:

- sensor errors (gain, orbital drift);
- irregularities of detector response and scan mode (variations in mirror oscillations);
- incomplete transmission of instrument and ephemeris data from the satellite to ground stations (Roy et al. 2002);
- incomplete instrument characterization and calibration knowledge (Roy et al. 2002);
- geo-referencing and re-projection uncertainties (datum transformation, spheroid definition);
- satellite velocity and altitude variations (roll, pitch and yaw);
- effects of the earth's rotation, curvature and elevation;
- data corruption in production, archival and distribution;
- software coding bugs and configuration failures;
- algorithm sensitivity and robustness;
- variable sun illumination geometry with respect to sensor position; and
- spatial and temporal variations in smoke, gaseous and particulate pollutants, light cirrus clouds, clouds, shadows, aerosols content and water vapor.

Image pre-processing refers to the set of procedures or corrections applied to the raw at-sensor measured radiances (Level 0 product) to correct for most of the above-mentioned artifacts. These corrections are performed as "bulk" processing either at ground receiving stations or onboard the satellite systems. In the case of MODIS, MLST performs all necessary corrections to generate directly usable VI products.

2.3.2.1 Atmospheric correction

Multiple sources of radiances, other than that of the target (the target is the vegetation canopy in this study), exert an influence on the observed spectral response recorded by the radiometer. The atmosphere affects the radiance measured at any point in an image by attenuating the energy reflected from a ground object before it arrives at the satellite, and by acting as a reflector itself, adding a scattered, extraneous path radiance to the signal detected by the sensor (Lillesand and Keifer 1994). Scattered upwelling path radiance from the atmosphere increases red reflectance, while atmospheric scattering and water vapor absorption tends to lower the NIR signal. The net result is a drop in NDVI signal as a function of aerosol content and an underestimation of the surface vegetation.

The dark target-based atmospheric correction (DTAC) approach has been utilized in the MODIS surface reflectance product. The atmospheric algorithm is applied to cloud free pixels (using MOD 03 cloud mask product) with a solar zenith angle of less than 75°. It corrects for gaseous absorption, molecules and aerosol scattering, the adjacency effects, and the coupling effect between the atmospheric and surface BRDF (Vermote et al. 2002). Adjacency effects, caused by variation in land cover, refer to the measured top-of-atmosphere (TOA) radiances not only coming from the target but also from the adjacent pixels. The correction procedure currently relies on readily available ancillary data from National Centers for Environmental Prediction (NCEP) for the digital elevation model (DEM), surface pressure, ozone and water vapor content inputs (Vermote et al. 2002). It also relies on MODIS data itself for aerosol optical thickness (AOT), and water vapor (MOD 05) input. The algorithm uses pre-computed coupling factors and atmospheric scattering properties stored in tables (Vermote 2004). It also uses a simplified function to compute gaseous transmission and pre-defined land BRDF signatures for an atmosphere/BRDF coupling correction (Vermote and Vermeulen 1999).

Figure 2-2 gives an overview of the atmospheric correction procedure for the MODIS data. A full description of the atmospheric correction process is provided by the MODIS surface reflectance Algorithm Theoretical Basis Document (ATBD) (Vermote and Vermeulen 1999).

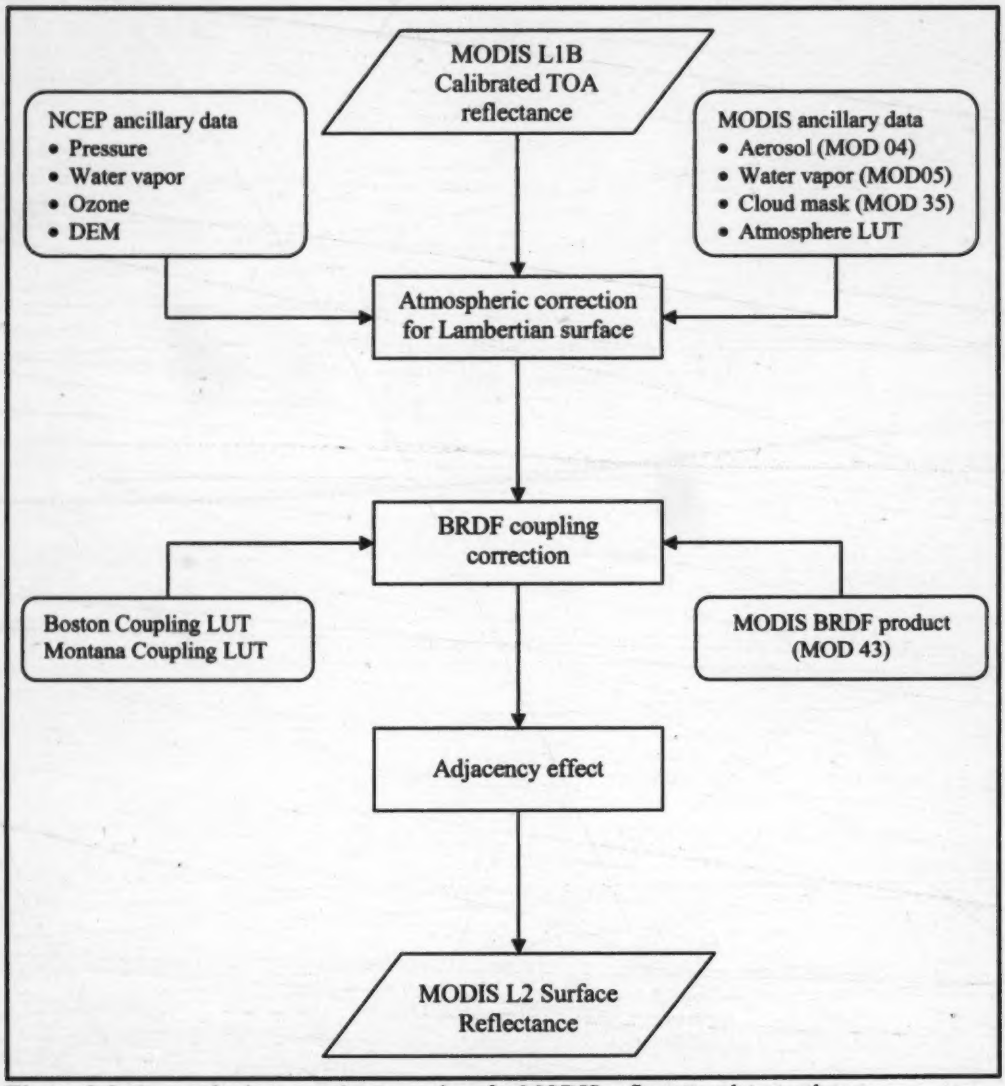

Figure 2-2: Atmospheric correction procedure for MODIS reflectance data product.

2.3.2.2 Geometric correction

Geometric correction addresses an image's spatial distortions introduced by the instrument sensing geometry, the curvature and rotation of the earth, surface relief, and perturbations in the motion of the sensor relative to the surface (Wolfe et al. 2002). The procedure first geolocates the sensed observations and then alters the data to correspond with true ground or image space in a known (or predefined) coordinate system.

MODIS geolocation is performed using a global network of ground control points (GCPs) to remove sensor orientation biases and trends (Wolfe et al. 2002). Exterior orientation (position and attitude) of Terra is measured in real time by sensors onboard the satellite, which enables geolocation of MODIS data to be approximately 150 m accurate at nadir. A global DEM (Logan 1999) is employed to model and remove relief distortion effects. The MODIS geolocation product is a Level 1 product and defines for each 1 km MODIS observation the geodetic latitude and longitude (WGS-84), terrain height, sensor zenith angle, sensor azimuth, slant range to the sensor, solar zenith angle and solar azimuth (Nishihama et al. 1997).

These geolocation data are also stored in the MODIS Level 1B (L1B) calibrated radiance products and in several MODIS Level 2 products as well as in the MODIS land L2G products (Wolfe et al. 1998). An estimate of the a priori root mean square (RMS) geolocation error is included in the metadata of every MODIS geolocation product. Nishihama et al. (1997) has provided detailed description about MODIS instrument geometry and geolocation algorithm.

2.3.3 Compositing

Although it is possible to collect data on a daily basis, it is rarely possible to consistently collect cloud-free data, especially over a large area. To overcome this problem, the composite imagery approach was developed. The compositing algorithm combines several images over a given time interval (16 days in this study) to create a single, cloud-free image with minimal atmospheric and sun-surface-sensor angular effects (Holben 1986), though the effects of translucent clouds and haze may not completely removed.

MODIS acquires the reflectance data from the earth's surface under varying solar illumination angles, sensor view angles, and atmospheric and cloud conditions. Variations such as off-nadir viewing and atmospheric aerosol content make direct comparisons between the radiance data difficult, and cause reductions in VI values (Holben and Fraser 1984). This situation led to the development of the technique called Maximum Value Compositing (MVC). The MVC algorithm selects the input pixel with highest VI value as output to the composited product. While it provides a solution, the

disadvantage of using this approach is the unpredictable pixel selection due to anisotropic (or bi-directional reflectance) influences of the earth's surface. It selects off-nadir pixels with large forward-scatter view angles, large solar zenith angles (Figure 2-3), and with greater value than their nadir equivalent value (Huete et al. 2002), which may not be cloud free or atmosphere clear (Goward et al. 1991; Moody and Strahler 1994; Cihlar et al. 1994 1997). This limits the use of VI composite products for consistent and accurate comparisons. Figure 2-3 illustrates MODIS data acquisition and the sun-canopy-sensor angles.

In case of MODIS, atmospheric correction prior to compositing and VI computation has an impact of more pronounced surface anisotropy effects. Therefore, the MVC is anticipated to dramatically increase the selection of off-nadir pixels, particularly over open canopies (FORWARD study area has open canopy), which exhibit higher NDVI values when viewed obliquely (Huete et al. 2002). To compensate for this, constrained view maximum value compositing (CV-MVC) was introduced.

CV-MVC method selects the maximum value VI closest to the nadir-view. Another scheme, Bi-directional Reflectance Distribution Function (BRDF), utilizes all of the acceptable quality bi-directional reflectance observations to interpolate to their nadir-equivalent reflectance values from which the VI is computed and produced. Alternative compositing approaches are averaging VI values (Meyer et al. 1995) and The Best Index Slope Extraction (BISE) (Viovy et al. 1992). Cihlar et al. (1994) and Qi and Kerr (1997) have discussed few other VI compositing techniques.

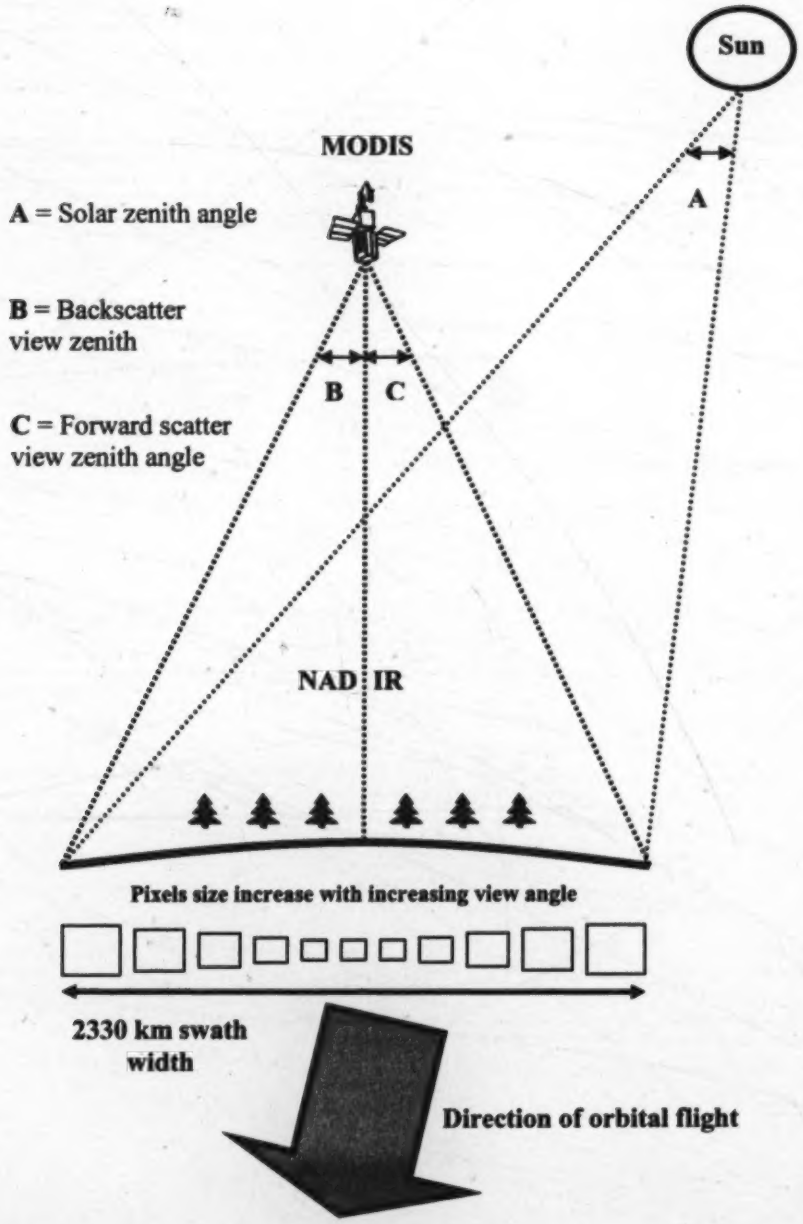

Figure 2-3: Illustration of MODIS data acquisition, sun-canopy-sensor angles, and increasing pixel size with the scan angle (developed from Huete et al. 1999).

2.3.4 Validation

The translation of radiometric VI's to biophysical, phenologic and change detection interpretations on the ground require validation efforts to assess error, uncertainty and performance. MODIS land products' validation is performed by analytical comparison of product samples with independently derived data from field based correlative measurements; output from canopy radiant transfer and bio-climatic models; experimental airborne measurements; and existing satellite data sets with established uncertainties (Justice et al. 1998). The goal is to provide a ground truth characterization of different land covers types to validate land products. For this purpose, the validation program leveraged and sought partnerships with existing sources such as science data networks and international research efforts. A summary of data sets used in MODIS VI validation is presented in Appendix A.

Measures of success for the accuracy and performance of VIs are assessed by conducting tests such as baseline, threshold and saturation VI value extraction, correlative measurements, seasonal profiles, transition zones, and in-situ nadir-based reflectance measurements over a global set of different validation sites. These validation or ground-truth sites are radiometrically and biophysically characterized and provide an infrastructure for the establishment of a semi-permanent array of EOS land validation, which includes a flux tower for long term time-series data collection of terrestrial biophysical dynamics (MODIS Land Team (MODLAND) 2004). Morisette et al. (2002) provides a description of the primary validation data sources and sites. Pre-launch validation efforts focused on testing the robustness of the algorithm with MODIS-like data sets (Huete et al. 1999) over a range of representative conditions. Data collected as part of the Boreal Ecosystem-Atmosphere Study (BOREAS) (BOREAS Information System 2004) has been used for VI validation over FORWARD study area. The data included MODIS Airborne Simulator (MAS) (1994) and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (1996) overflights over the Boreal forest in growing and snow covered seasons; and field biophysical and radiometric (Parabola-SE-590) measurements with sun photometers. Post launch validation efforts include an airborne radiometric system for rapid and low cost land production validation called MODLAND Quick Airborne Looks (MQUALS). Detailed information about the MODIS land

validation is provided by MODIS Land Team (2004), Morisette et al. (2002) and Huete et al. (1999).

2.3.5 Quality Assurance (QA)

Product performance information is required to consider the VI imagery in their appropriate scientific context. The MLST has developed detailed procedures to evaluate the VI data quality with respect to their intended (or anticipated) performance through quality assessment and validation activities. The scientific quality of data products is documented and stored in the MODIS VI file at the pixel level and as metadata at the product file level (Roy et al. 2002). These results are generated in the production algorithm and by post-production assessment (Roy et al. 2002) to help users to filter data that is unsuitable for their applications and to develop error estimates. Data products are re-processed several times because error may be introduced at any time during the instrument life and may not be identified for a considerable time (Land Data Operational Product Evaluation (LDOPE) 2002). Therefore, once QA has been performed, any product issues identified later are posted online on the Known Product Issues Website (LDOPE 2004). Product cases are categorized as "reopened", "closed", "note" or "pending" and are updated by LDOPE personnel to reflect current status (Roy et al. 2002).

2.3.5.1 Pixel level quality

The MODIS VI product includes two QA science data sets (SDSs) namely 250 m 16 days NDVI Quality and 250 m 16 days EVI Quality. These layers are raster images of the same dimensions and identical format as the NDVI and EVI data images. Each pixel consists of a 16 bits field that reflects conditions under which it was acquired and processed (Huete et al. 1999). Table B-1 and Figure B-1 in Appendix B lists the names of the bit-fields, numbers of bits assigned to each bit-field and the bit combinations and corresponding descriptions.

2.3.5.2 File level quality

VI product quality information is provided as metadata objects in the accompanying metadata file. These objects summarize tile-level data quality and are useful for ordering, screening and assessing purposes. Table B-4 in Appendix B provides

the list of 18 metadata objects accompanying the MODIS VI product, characterized by five attributes namely object name, object type, group name, description and level. Table B-2 in Appendix B provides the relationship between the per-pixel QA bits and QA SDS metadata objects. Table B-3 in Appendix B presents the VI Usefulness Index scaling method. Detailed understanding of QA analysis, definition, scope and approach is provided by Huete et al. (1999), Roy et al. (2002), and MLST (2004).

Chapter 3

Literature Review-II

This chapter addresses the role of vegetation phenology in forested ecosystem monitoring. The review focuses on past remote sensing efforts to model vegetation seasonal changes, different methods employed to derive satellite phenological parameters, and time-series data quality considerations for phenological studies.

3.1 Phenology

Phenology is the study of the periodic biological occurrence of animal and plant phenomena in relation to the weather and climate. Daubenmire (1968) defined phenology as the relationship of the seasonal sequence of climatic factors to the timing of growth and reproductive phases in vegetation, such as the initiation of seasonal growth, time of blooming, time of seed set, and the development of new terminal buds. However, the U.S. International Biological Program Phenology Committee suggested a broader definition of phenology: "the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species" (Lieth 1974).

Phenological records have a history of more than 300 years in Europe and involved noting the first dates of such exciting observations as the flowering and budburst of native plants, the appearance of butterflies, the arrival of swallows, and hearing a cuckoo. In Canada, extensive phenological observations were initiated by the Royal Society of Canada in the 1890's. Alberta has phenological records of native species since 1973. Plantwatch, initiated in 1995, is a successor to Alberta's previous phenology initiative, Alberta Wildflower Survey, which started in 1987 and involved 200 volunteers reporting on three flowering stages for 15 native plants (Beaubien 2000). Plantwatch was expanded in 2001 by adding more plant species and establishing linkages to Environment Canada and the Canadian Nature Federation as well as involving representatives from all

provinces (Beaubien 2000). Data tables and maps of budburst times are maintained by the University of Alberta Devonian Botanic Gardens and are updated regularly online (Beaubien 2004).

3.2 Phenology: Indicator of Stress and Measure of Ecosystem Resilience

The timing and progression of canopy development may help to infer the conditions of plants relative to their environment, including soil moisture, soil temperature, illumination, air temperature, weather and precipitation (Reed et al. 1994). Vegetation growth dynamically responds and adapts to prevailing environmental conditions. The dynamics are manifested as changes in the distribution of vegetation types, plant growth and development (Belward 1991). Liebig's law of minimum states that "plant growth is limited by a single resource at any one time; only after that resource is increased to the point of sufficiency can another resource enhance plant growth". However, if plants compensate for resource imbalance in the environment, growth should be equally limited by all resources (Bloom et al. 1985). Factors such as seasonal reductions in temperature, mild frosts, photoperiodic effect of reduced seasonal day length mediated by phytochrome, drought, flooding and nutrient deficiency, increase rate of leaf senescence. On the other hand, high nitrogen levels and high concentrations of zinc, iron, chlorine, and iodine decrease the rate of senescence (Ontario Forest Research Institute (OFRI) 1997). If younger foliage in an evergreen tree exhibits early senescence, it is likely that the tree is suffering from fairly large imbalances of nutrients or some other stress (OFRI 1997). Similarly, changes in soil fertility, site quality, forest succession, and species composition in relation to abiotic and biotic disturbances such as severe climatic conditions, fire, pathogenic organisms including insects and diseases, foraging animals and competing vegetation significantly affect the growth and hence alter the phenological transition dates of canopy growth (Weetman 1983). Moreover, stresses such as air pollutants, ozone, herbicides, pesticides and fertilizers and intentional intervention such as harvesting or the implementation of silviculture practices, reforestation, protection or conservation programs etc. may have positive or negative impacts on plant growth.

Reed et al (1994) reported that temperature, photoperiod and moisture play a vital role in the photosynthetic activity of the deciduous and coniferous forested landscape

with specific adaptations of different species. Nienstaedt (1974), too, demonstrated that temperature plays a major role in the control of phenological response of North American tree species. Particularly in the Boreal region, the start of the vegetation growth period is usually related to temperature (Cannell and Smith 1986) because the ecosystem is limited by radiation rather than by moisture. Evapotranspiration increases with increasing temperatures causing excess water loss which can severely stress trees. Consequently photosynthesis may decline or level off. Changes in photosynthetic rates influence carbon and nutrient assimilation and water use which act to re-allocate resources towards maintaining vigor, growth, reproduction and defense functions (Browning 1995; Cannell and Jackson 1985; Ross and Pharis 1985; Stephenson 1981). In temperate zones of the earth, timing of spring growth phases, for example, budding, leafing, and flowering of plants, is primarily a response to accumulated temperature above a threshold value (Beaubien and Freeland 2000). Short days also induce dormancy in woody plants (Vegis 1964; Nooden and Weber 1978). With critical day length being a function of latitude, northern populations become dormant while southern species continue to grow for the same day length (Oleksyn et al. 1992).

Changes in phenological events may therefore be indicative of important year-to-year climatic variations and even global environmental change (Reed et al. 1994). In Canada, a linear trend increase of 0.8 °C in summer (Environment Canada 2004*a*) and 1.2 °C in spring (Environment Canada 2004*b*) temperatures from 1948 to 2004 have been observed. Specifically in western Canada, summer and spring warming of 0.9 °C to 1.7 °C has been observed over the last century (Gullet and Skinner 1992), as opposed to parts of eastern Canada. Plantwatch flowering data also reflects this change, with timing of first bloom (10% pollen shed) of Aspen poplar (*Populus tremuloides*) in Edmonton, Alberta now occurring almost a month earlier than it did a century ago (Beaubien 2000). Beaubien (2000) reported El Nino as one of the factors causing the earlier bloom times. Moreover, January temperatures are rapidly warming in the Canadian Prairie Provinces (Chapman and Walsh 1993). It is anticipated that the climate warming will disrupt the local adaptation of plants to a combination of thermal and photoperiod regimes since it contributes only to heat accumulated and doesn't affect photoperiod at all (Lechowitz 1995).

The above literature suggests that because vegetation phenology is responsive to both climate and human disturbances, it may serve as a good indicator of ecosystem health and as a means to measure cumulative stress in an ecosystem. In addition, it integrates and reflects the response of the earth's biosphere to inter- and intra- annual climate dynamics and hydrologic regimes (Myneni et al. 1997). Therefore, phenological information has the potential to provide us with a measure of ecosystem resilience. It is for these reasons that vegetation phenology is considered as core variable for the monitoring of environmental change by Environment Canada's Ecological Monitoring and Assessment Network (EMAN) (EMAN 2003), established in 1994.

3.3 Remote Sensing and Phenology

Until recently, most work on phenology studies has been limited to individual animal or plant species. With the advent of high temporal global satellite imagery, data is now available to examine and monitor biome and ecosystem level phenological event changes. This has led to a new interdisciplinary science of landscape ecology. Vegetation phenology/dynamics monitoring on both regional and global scales is concerned with community, biome and ecosystem levels of organization. A single satellite observation in time, then, is of limited use in successfully characterizing the ecosystem dynamics and classifying vegetation except in areas of low dynamic activity (change in density, color, or canopy architecture of a vegetation canopy that manifests itself as changes in chlorophyll and other light absorbing pigments discernible by satellite sensors).

3.3.1 Satellite versus ground based phenology observations

Satellite derived phenology is fundamentally different from traditional ground based observations. The phenological response to environmental variables varies according to the species and location factors such as elevation and aspect of the plant community. Satellite sensors have not yet achieved high enough spatial resolution in conjunction with the high temporal resolution to detect such phenological events of individual species as leafing, budding and flowering, though, these sensors are still capable of measuring broad scale changes in the landscape that are indicative of ecological health. Satellite detection of phenological stages is a subjective process (White et al. 1997). It is very difficult to objectively define an absolute start and end of a

growing season (onset of greenup and senescence (OGS)) from satellite observations (White et al. 1997). The strict definition of greenup onset depends on the objectives of a study but they roughly point towards the same concept as of budburst, flowering and blooming used in ground-based phenological studies. However, OGS avoid connection to the field phenology measurements and imply the concept of satellite based phenology. Satellite based phenology accounts for pixel level activity rather than species specific activity. Each pixel represents the composite response of several vegetation communities (possibly mixed with non-vegetated surfaces e.g. water bodies) sampled over an area equal to the spatial resolution of the imagery (in this case 250 m x 250 m). Overall, linkage between these two types of phenological information yields a better understanding of how climate induced individual species-level responses aggregate to larger scales (Zhang et al. 2004).

3.3.2 RS phenological research review

Phenology is highly variable (Schmidt and Lotan 1980) and responds to long term variation in climate (Sparks and Carey 1995). Phenological signals can be influenced by various local and genetic factors, permitting plants to serve as a reliable indicator of environmental change (Schwartz 1997), especially temperature variations in the spring season (Myneni et al. 1997; Schwartz 1999). Therefore spring plant phenology data is extremely useful in monitoring climatic variation.

A number of studies focusing on the analysis of global and continental-scale vegetation patterns using NOAA AVHRR data were initiated in the mid 1980s. For example, Goward et al. (1987) studied selected biomes in North and South America and observed that temporal variations of similar vegetation types were correlated to known climatology of the continents; in 1990 Lloyd employed phenological classification of global vegetation cover in which classes were defined in terms of timings, duration and intensity of photosynthetic activity derived from multi date AVHRR NDVI data using a supervised binary decision tree.

Reed et al. (1994) computed twelve key Vegetation Phenological Metrics (VPMs) using NDVI 1 km data derived from NOAA AVHRR sensor. Data was collected from 1989 to 1992 over conterminous United States (U.S.) and a strong coincidence was

observed between satellite derived phenological metrics and expected phenological characteristics of known land cover types. In particular, these metrics were successful in characterizing the phenology of four types of grasslands and spring wheat in North Dakota, and differentiating between coniferous and deciduous forest stands. These results validated the significance of VPMs and portrayed these as potential tools for monitoring global environmental change. They further postulated that an increase in variability of deviation of VPMs in a region may be a signal to conduct more detailed land cover assessment with high resolution imagery and ground truthing. The authors mentioned that some metrics have more applicability for selected land cover types and may have shortcomings for others. For example, the time integrated NDVI metric was identified to have shortcomings in coniferous dominated regions whereas rate of greenup and senescence effectively discriminates between deciduous and coniferous stands.

In another study Reed and Schwartz (1999) used AVHRR NDVI 1 km data for the period 1990-1995 over conterminous U.S. to report correlations between satellite derived phenology and ground-based modeled phenological outputs. First leaf and first bloom dates were found to be positively correlated with sensor detected onset of greenness dates. Correlations were strongest for deciduous forests ($r = 0.62$) and mixed woodlands ($r = 0.64$), intermediate for tall grass ($r = 0.46$) and lowest for short grass ($r = 0.37$). However, a consistent earlier onset of greenup dates were detected by the AVHRR sensor when compared to modeled first bloom date across all land cover types. This finding led authors to suggest that AVHRR detects understorey greenup in the forest rather than overstorey species greenup. The low bi-weekly temporal resolution of satellite data and the relatively invariant climate of the years between 1991 and 1995 were identified as utility limiting factors of the analysis. For example onset dates in four out of five years in the Harvard forest site were all registered in the same bi-week thus making annual variability among most sites undetectable by the sensor.

Senay and Elliot (2000) characterized the spatial and temporal dynamics of Oklahoma vegetation using AVHRR bi-weekly NDVI data from 1990-1996 over the conterminous U.S. The authors identified dates and relative magnitudes for onset of greenness as well as peak and senescence for four land cover types, and reported a high

inter-annual variability in the peak date and magnitude among the land cover classes compared to almost none for onset and senescence metrics. Moreover, they concluded that AVHRR NDVI was successful in discriminating rangelands with different canopy densities consistently across the years.

Roerink et al. (2003) quantified the impact of climate variability on vegetation dynamics using AVHRR NDVI 1 km data over part of Sahelian Africa and Europe and found that for dry areas, both the total amount of vegetation and the seasonal difference between dry and wet season increase with increasing precipitation. However, for wetter regions, the seasonal difference remains almost constant. Based on these observations, authors concluded that in wetter regions both precipitation and net radiation are the limiting factors for the vegetation growth.

Duchemin et al. (1999) used AVHRR NDVI 1 km data from 1989-1994 over deciduous forest located in France to monitor the OGS on three species. They found a good correlation between the satellite-derived budburst and budburst timing predicted from air temperatures using the thermal time model.

Lee et al. (2002) used AVHRR NDVI 1 km data from 1981-1991 over Inner Mongolia Autonomous Region (IMAR) to evaluate the relationships between vegetation phenological patterns and climatic variation. They built on the work done by Myneni et al. (1997) who used the same data from the same time period over northern hemisphere vegetation located between 45° N and 70° N latitude to asses the impact of climatic trends on vegetation. Onset of greenup was found to have advanced by 7 to 10 days from 1981-1991. They argued that earlier onset of greenup was associated with increased spring temperatures and earlier uptake of atmospheric CO_2. Lee et al. (2002) investigated vegetation phenological changes at lower latitudes such as IMAR located between 39° N and 49° N latitude. Little or no change in the date of onset of greenup was observed over forested and cultivated landscapes. Monthly mean temperature and precipitation measurements were claimed to successfully explain the difference in onset of greenup patterns.

Griffith et al. (2002) used AVHRR NDVI 1 km data for the year 1995 over Nebraska, Missouri and Kansas to seek interrelationships between VPMs and selected

Water Quality (WQ) variables which included conductivity, turbidity, total phosphorus, and nitrate-nitrite nitrogen. 290 stream sites were randomly selected in Kansas, Nebraska and Missouri and were sampled once by the U.S. Environmental Protection Agency (EPA) Region VII during the late spring and summer of 1994 and 1995 as part of its Regional Environmental Monitoring and Assessment Program (REMAP). VPMs were derived from time series NDVI data using algorithms modified from Reed et al. (1994). Spring NDVI values, mean date of onset of greenness and standard deviation of NDVI values at the onset of greenness were found to have the greatest number of significant correlations (r values up to 0.8) with stream WQ parameters. Peak NDVI date and magnitude were found to be frequently correlated with Index of Biotic Integrity and Habitat Index. Authors reported the potential for estimating summer WQ conditions using spring AVHRR NDVI data and supported Jones et al. (1997), who found that change in NDVI values over a 15 year period over U.S. Mid-Atlantic States was useful in assessing the watershed's relative vulnerability to conditions that affect stream water quality. They further built on land use/land cover (LULC) and water quality relationship studies (such as Omernik 1976; Osborne and Wiley 1988; Lenat and Crawford 1994; Roth et al. 1996; Allan et al. 1997; Johnson et al. 1997; Basnyat et al. 1999) and found that VPMs are more highly correlated to the WQ than were the LULC proportions. They argued that studies relating LULC to WQ employed traditional temporally static land cover maps and does not account for phenological, inter-annual or successional (human induced) changes. They pointed out that watershed boundary delineation, positional accuracy of the sampling point and general digitizing artifacts can introduce significant errors in the results. A major weakness identified with this study was potentially unreliable WQ data, since each stream was sampled only once. And, in some cases the year of water sampling did not even match the year of NDVI data acquisition. Despite these weaknesses, this research was claimed to be the first demonstration of empirical NDVI-stream WQ relationships on a regional, multi-state scale.

Zhang et al. (2004) used MODIS EVI 1 km data for the period from January 1 to December 31, 2001 to identify vegetation phenological transition dates and link these to MODIS land surface temperature (LST) data from the northern hemisphere between 35°N and 70°N. The onset of greenup was found to be 4 to 9 days earlier and onset of

dormancy 2 to 16 days later for urban areas compared to adjacent natural forests. Authors reported that urban heat island effect, which results in 1 to 3 °C higher mean annual temperature in urban relative to rural areas, caused the difference. The growing-season length for forests was found strongly correlated with variation in mean annual LST.

The above studies indicate that time-series VI data are very useful for surveying vegetation status and that meaningful conclusion can be derived regarding the ecological conditions of the landscape.

3.4 Methods Used to Detect Phenology from Satellite Data

During the last decade a number of different methods have been adopted by researchers to characterize the seasonality of time-series VI data and to identify the timing of OGS and other derived metrics. These methods had considerable associated problems in identifying phenological key stages and have evolved since then.

3.4.1 Specific NDVI thresholds

This method uses a specific NDVI threshold value applicable across land covers at which the vegetation activity is assumed to begin: for example Fischer (1994) used 0.17, Markon et al. (1995) used 0.09 and White et al. (1997) used 0.5 NDVI threshold value to extract onset of greenness. Lloyd (1990) used 0.099 as threshold NDVI value which was the maximum value reported for Kenyan bushland in the period immediately before the growing season (Justice et al. 1986). The author points out that this threshold value needs testing in order to be applicable to a range of ecological zones. The constant threshold value is also species specific and varies with soil background and illumination conditions (Reed et al. 1994). Therefore it is not possible to establish a single meaningful NDVI threshold value for different land cover types at which vegetation activity is assumed to begin on the landscape.

3.4.2 Backward looking moving averages

This method adopted from Auto Regressive Moving Average (ARMA) models (Hoff 1983; Granger 1989) uses a comparison to a moving average of the time-series to identify departures from an established trend (Reed et al. 1994). This approach identifies the point where NDVI exhibits a sudden increase which is assumed to be the start of photosynthetic activity, though, measuring the beginning of the greatest increase in

NDVI during the start of the year may not correspond to the actual onset of greenness in case where land is covered by snow (Reed et al. 1994). A satellite sensor would signal the snow melt event as the greatest increase in NDVI which, in reality, is not onset of greenness. The authors also identified the potential problems with the running median method employed as a data smoothing technique. This method served well at minimizing the effects of extremely low NDVI values that were related to cloud contamination, but had the undesirable effect of presumed valid NDVI peaks. Reed and Schwartz (1999) updated the technique by incorporating an upwardly biased smoother to take advantage of "clean" high NDVI values, while smoothing lower values. Reed et al. (1994) have discussed this method in detail.

3.4.3 Largest NDVI increase

Kaduk and Heinmann (1996) used the largest increase in the NDVI time-series data, after the monthly mean temperature had reached 5°C, as an indication of budburst. The point corresponds to the onset of greenup. This method has the same problem of misinterpreting the snow melt event as 'largest NDVI increase' and is not applicable to land covered with snow at the start of the growing season.

3.4.4 Empirical equations

Moulin et al. (1997) used empirical equations to derive the start, the peak, the end and the length of vegetation cycle using AVHRR NDVI 1 km dataset for the year 1986. These equations included terms accounting for mean (mean NDVI term) and shape (derivative term) of NDVI signal. A soil threshold and a slope coefficient used in the algorithm were empirically set. A detailed description of the equations and considerations involved can be found in the Moulin et al. (1997). The authors reported that for the Boreal regions the detected onset of greenup corresponded to the date of snow melt. This observation can be linked to the findings of the Reed and Schwartz (1999) who attributed the under storey detection of the satellite sensor to the NDVI algorithm and not to the onset of greenup detection method employed.

3.4.5 Zhang method

Zhang et al. (2003) method used piecewise logistic functions, which are fit to remotely sensed VI data. Onset and dormancy transition dates corresponded to the time at

which rate of change in curvature in the VI data exhibited local maxima or minima. This approach builds on the approach used by Badhwar (1980, 1984), who fit exponential and logistic smooth functions of time to extract the spectral reflectance variation for corn and soybean crops during growth stages. Authors claimed that this approach is well suited for global application and ecosystems characterized by multiple growth cycles within a single growth season (common for croplands and semi-arid regions). It also provides vegetation phenology monitoring in near real time and does not require pre-smoothing of the VI data or the use of a threshold VI value. A detailed description of the method is presented in Zhang et al. (2003).

3.4.6 Zhang modified method

The original Zhang's method relies on determining only the extreme point (maxima or minima) in the curvature rate of change of the function using the formula given by Zhang et al. (2003). This method was modified in a way that the point of maximum second derivative of the best-fit logistic function was also determined. The second point tended to occur a bit later than Zhang's point. Onset of greenup date was then determined by averaging the two dates obtained from the two points (Yu et al. 2004). The averaging had an effect of producing a smoother map, which was desirable.

3.5 Time Series Data Quality Considerations for Satellite Phenological Studies

The correct interpretation and meaningful extraction of conclusions from long-term time series of RS data requires the ability to discriminate between product artifacts and changes in the earth processes being monitored (Roy et al. 2002). For results to be comparable over time and location, time-series VI values should contain no spatial pattern that can be attributed to the random and systematic error in the data, though quantifiable spatially dependent systematic and random error may be present.

Previous RS phenology studies employed Landsat Multi Spectral Scanner (MSS) (79 m) and Landsat Thematic Mapper (TM) (30 m) sensors. For example, Odenweller and Johnson (1984) compared Landsat MSS time-series data to the expected phenological characteristics of different crop types to perform crop classification. Issues such as a 16 day repeat cycle, which represents too large a time step in the data to reliably

assess VPMs, and cloud and haze contamination restricted the ability of these sensors to track key phenological events. The problem was solved by the launch of a high temporal resolution AVHRR sensor that collected data every day. Moreover, scientists came up with AVHRR data compositing approach to remove the cloud contaminated pixels from the imagery but calibration errors, poor geometric registration, cloud screening difficulties, less sophisticated compositing algorithms and the presence of off-nadir distorted pixels made AVHRR NDVI data not an optimum choice for vegetation monitoring applications (Goward et al. 1991). AVHRR was never designed for land applications and the operational VI products are based on the current needs for weather forecasting (Justice et al. 2002). Kasischke and French (1997) used AVHRR NDVI 1 km from 1990-1992 over Alaska and reported the critical constraints on the use of AVHRR data to map and monitor changes in vegetation for the Boreal landscape. These constraints included the effects of cloud and atmospheric haze, fire on forest succession, and forest stand patch size with respect to system resolution. Heterogeneous patches of forests smaller than the cell size of the AVHRR sensor in the study area would result in significant sub-pixel mixing (Kasischke and French 1997). Authors regarded Landsat TM spectral bands as superior to that of AVHRR for land cover applications. In addition to that, studies have shown that AVHRR instrument calibration has changed significantly following launch and drifted subsequently over time, which introduces the inter-annual variability in VI data unrelated to vegetation biophysical dynamics (Che and Price 1992; Kaufman and Holben 1993; Rao 1993; Teillet et al. 1990).

These artifacts make the AVHRR data not well suited for time-series vegetation phenology studies where induced data trend will be the result of faulty sensor calibration and cloud effects rather than the parameters under focus i.e. phenology and inter-annual weather changes.

3.5.1 Why use MODIS VI data

The growing need to precisely characterize vegetation dynamics led to the launch of a new earth observation satellite sensor MODIS that has higher spatial and spectral resolution. The MODIS EVI product provided the land research community with the flexibility to move beyond its dependence on the NDVI. The land bands have a heritage

from the Landsat TM, with capabilities added in short-wave and long-wave infrared (Justice et al. 1998). MODIS data is well suited for the regular monitoring of forested ecosystems because:

- it is cost effective (currently the distribution of MODIS data is free of any cost);
- a large amount of effort has been put into the development of directly usable products i.e. the MODIS Land Science Team (MLST) is funded by NASA to develop the science algorithms and processing software used to generate an extensive set of land vegetation products such as NDVI, EVI, LAI, fAPAR etc. (Roy et al. 2002);
- MODIS land products quality is ensured by calibration, Quality Assurance (QA), and validation activities, which form an integral part of the MODIS land production chain;
- the seven "land" bands (from band 1 to 7) in MODIS are carefully chosen to minimize the impact of atmospheric gases' (particularly water vapor) absorption (Vermote et al. 1997) since canopy spectral signature is not only different at the ground level (no atmosphere) compared to satellite sensor level, but also varies temporally from image to image because the atmosphere and climate change with time;
- the atmospheric correction of MODIS provides a systematic aerosol correction at 1 km (Vermote et al. 2002), constituting a considerable advance on AVHRR Pathfinder dataset, which only relied on operational Rayleigh (standard atmosphere with zero or constant aerosol loading) and ozone effects correction;
- MODIS multiple OBCs for the calibration of the solar reflective regions accomplish a higher precision calibration. Additionally, they are periodically validated through vicarious calibration techniques for detection and correction of drift in calibration gains over time (Barbieri et al. 1997);
- knowledge of sun-canopy-sensor geometry is embedded as imagery in the MODIS VI data since MODIS viewing angles vary ±55° cross-track accompanied by solar illumination angle differences of up to 20° from edge to edge of the MODIS swath

(Huete et al. 1999). The variable scan angles cause MODIS pixel dimensions to change, cross-track and along-track. For example for 0° pixel dimension is 250 x 250 m; for 15° - it is 270 x 260 m; for 30° it is 350 x 285 m; and for 45° it is 610 x 380 m (Huete et al. 1999). This generates another source of error in the VI time-series data. Sun angles and variable pixel dimensions are illustrated in Literature Review-I section in Figure 2-3; and

- finally, spatial resolution of 250 m is suitable for characterizing the vegetation phenology for the FORWARD study area since average patch size is roughly about 0.4 km^2 which is greater than the individual pixel area of 0.0625 km^2.

3.5.2 MODIS current status

Wolfe (2003*a*) reported that Terra MODIS has been stable for over 26 months (after its launch) and there are no indications of problems other than failure of a power supply system, which was replaced. Current geolocation is very accurate (~50 m) and OBCs proved to be valuable for on-orbit characterization. Given this, deep-space maneuver is still needed to better characterize angle-of-incidence (AOI) response (Wolfe 2003*a*).

Chapter 4

Materials and Methods

4.1 Brief Description of the Study Area

This study has been carried out in 16 watersheds in the western Canadian Boreal Plain ecozone that extends southeast from north-eastern British Columbia through north-central Alberta and Saskatchewan to southwestern Manitoba. The geographic position of the study area lies at 54° 10' 6.6"-N Lat and 115° 34' 21"-W Long. Figure 4-1 shows the study area's location and the 16 test watersheds. Data about these watersheds has been collected as part of the FORWARD project.

The Boreal Plain ecozone is composed of a variety of forest species, including evergreen conifers such as Black spruce (*Picea mariana* (Mill.) BSP), White spruce (*P. glauca* (Moench) Voss), Lodgepole pine (*Pinus contorta* Dougl. ex Loud. Var. *latifolia Engelm*), Jack pine (*Pinus banksiana* Lamb), and deciduous hardwoods such as Balsam poplar (*P. balsamifera* L.) and Trembling aspen (*Populus tremuloides* Michx.). Soils in this ecozone are predominantly of sandy clay loam and many meters of deep unconsolidated clay loam glacial till, overlain primarily on sedimentary bedrock (Smith et al. 2003*b*). While the forest floor is generally covered with humus, the underlying strata are dominated by soils of Luvisolic order, and Gleysols, Brunisols, and Regosols are present as well (Ecological Stratification Working Group 1996). Organic and Gleysolic soils are associated with poor drainage (e.g. peatlands) areas while Luvisolic and Brunisolic soils occur on well drained sites (Strong and Leggat 1992). In addition, glaciofluvial, lacustrine, alluvial, and eolian deposits are also present, with textures that vary with the deposition process (Strong and Leggat 1992).

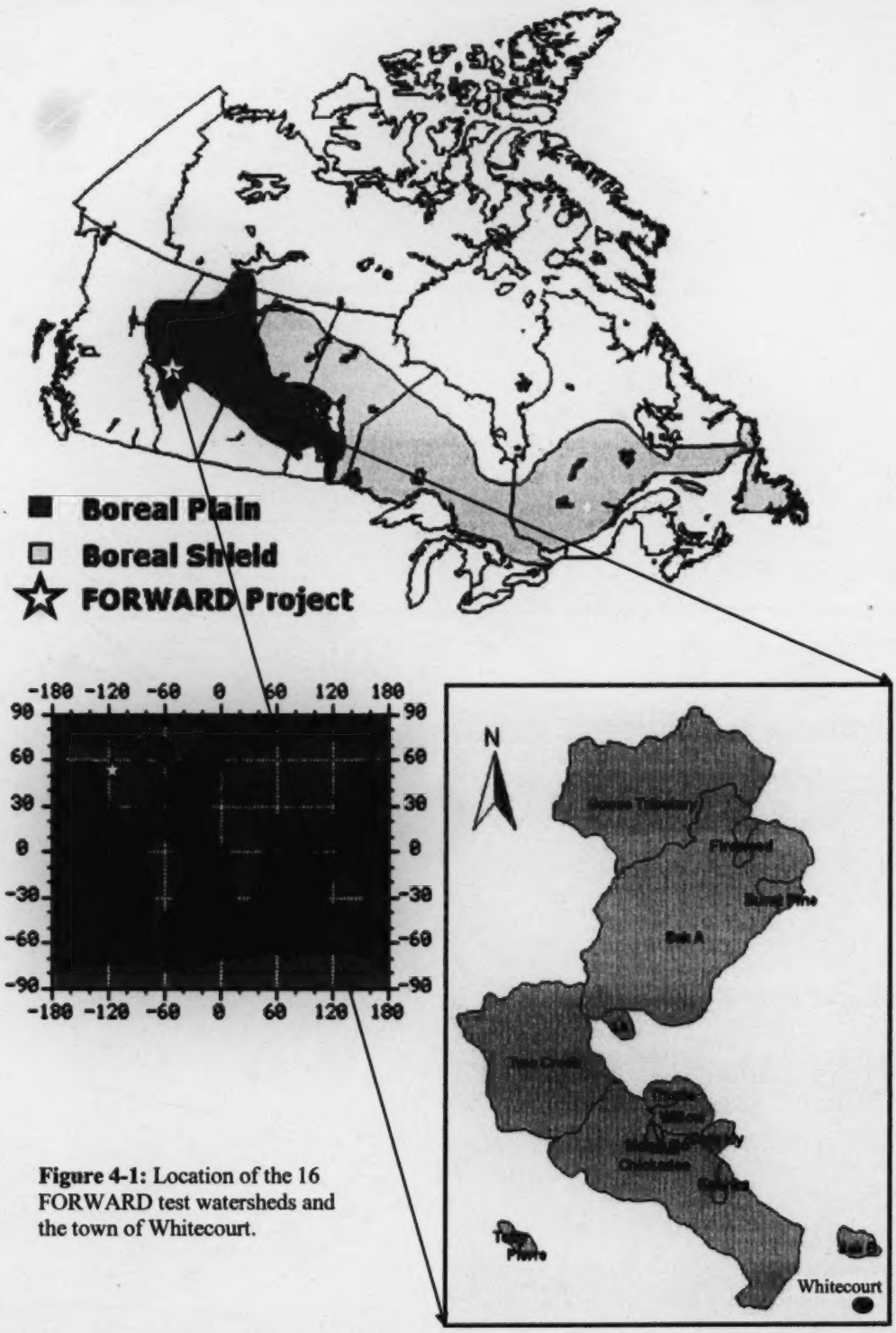

Figure 4-1: Location of the 16 FORWARD test watersheds and the town of Whitecourt.

Climate for this ecozone is continental, with long cold winters and short warm summers (Smith et al. 2003*a*) and relatively low annual precipitation (Strong 1992). Low albedo causes a greater heating of the overlying air mass relative to that over the Arctic Tundra, leading to a significant warming of the regional climate (Foley et al. 1994; Bonan et al. 1995). The mean July temperature is about 16 °C to 17 °C, with -20 °C being the mean January temperature (Saskatchewan's State of the Environment Report 1995); precipitation varies from 300 mm in Northern Alberta to 625 mm in southwestern Manitoba (Ecological Stratification Working Group 1996).

For the study area in particular, the highest mean monthly air temperatures and precipitations from 1939 to 1990, were recorded in July (Environment Canada 2003). The mean July air temperature at Whitecourt in Alberta, close to the study area location (54° 02'-N 115° 43'-W, Elevation: 1201 m) was 13.9 °C, and the mean July precipitation was 123.7 mm (Environment Canada 2003). The maximum 24-h precipitation of 91.8 mm was recorded on June 23 1985 (Environment Canada 2003). The mean air temperature for the period 1971 to 2000 at the Whitecourt airport location (54° 8'-N 115° 47'-W, Elevation: 782.4 m) in Alberta was -12.1 and 15.7 °C in January and July (lowest and highest for the year), respectively, and the mean annual precipitation was 577.7 mm, of which 30.8% occurred as snow (Environment Canada 2004*c*). The maximum 24-h precipitation of 98.6 mm was recorded on August 2 1989 (Environment Canada 2004*c*). Figure 4-1 illustrates the location of Whitecourt with respect to the study watersheds, where Environment Canada's weather stations are located.

4.2 Data Collection

4.2.1 Remote sensing data

A sequence of 4 years, from 2000 to 2003, of gridded MODIS VI (NDVI & EVI) dataset was used in this study. The dataset comes in Hierarchical Data Format - Earth Observing System (HDF-EOS), which is the standard archive format for EOS Data Information System (EOSDIS) products (MLST 2004). HDF-EOS is a multi-object file format and supports a variety of data types such as n-dimensional scientific data arrays, tables, text annotations, several types of raster images and their associated color palettes, and metadata. MODIS VI HDF-EOS file size is approximately 500 MB and consists of

11 Science data sets (SDSs), which are the actual data stored in array format (2-D, 3-D and even 4-D) (MLST 2004). Table 4-1 provides data field descriptions, data types, scale, valid range and fill values for the MODIS VI SDSs.

Table 4-1: Data filed descriptions of MOD13Q1 SDSs (Huete et al. 1999).

Data field	Name	Data type	Scale	Valid range	Fill value
DataField_1	250 m 16 days NDVI	INT16	10000	-2000 to 10000	-3000
DataField_2	250 m 16 days EVI	INT16	10000	-2000 to 10000	-3000
DataField_3	250 m 16 days NDVI Quality	UINT16	N/A	0 to 65534	65535
DataField_4	250 m 16 days EVI Quality	UINT16	N/A	0 to 65534	65535
DataField_5	250 m 16 days red reflectance	INT16	10000	0 to 10000	-1000
DataField_6	250 m 16 days NIR reflectance	INT16	10000	0 to 10000	-1000
DataField_7	250 m 16 days blue reflectance	INT16	10000	0 to 10000	-1000
DataField_8	250 m 16 days MIR reflectance	INT16	10000	0 to 10000	-1000
DataField_9	250 m 16 days average view zenith angle	INT16	100	-9000 to 9000	-10000
DataField_10	250 m 16 days average sun zenith angle	INT16	100	-9000 to 9000	-10000
DataField_11	250 m 16 days average relative azimuth angle	INT16	10	-3600 to 3600	-4000

The first two layers of MOD13Q1 HDF-EOS file are the EVI and NDVI images. These are 16-day composite, re-sampled, 250 m spatial resolution, 4800 x 4800 rows/columns, cloud-free, pre-processed (see Figure 4-3) high quality imagery VI pixels, produced for each year since 2000. Although the valid range of NDVI or EVI is from -0.2 to 1, the values are scaled up by a factor of 10,000 with a fill value of -3000. Corresponding scales, valid ranges and fill values for other SDSs are also shown in the Table. The next two layers provide the NDVI and EVI per-pixel quality information followed by the four SDSs of reflectance data from which NDVI and EVI are derived. This provides users with the flexibility to change the co-efficient values in the EVI equation or modify the algorithms in relevance to the regional conditions. The last three SDSs provide the sun-canopy-sensor angles. This information is needed to know the variable scan geometry under which the pixel reflectances were measured by the MODIS sensor.

Each SDS (or layer) is a tile unit (fixed-area size) in the Sinusoidal (SIN) grid projection. The tile unit is the smallest unit of MODIS land data processed at any time and has an aerial extent of approximately 1200 km x 1200 km (10^{o} x 10^{o}). The tiles are defined in a global non-overlapping grid such that there are 460 tiles, of which 326 contain land pixels (LDOPE 2003*a*). Vertical and horizontal coordinates of each tile are represented in the product filename. The tile for the FORWARD study area was identified as h11v03. Sinusoidal grid bounding coordinates of the h11v03 tile are -140° to -93° 19' 49.8" Long, and 50° to 60° Lat (Wolfe 2003*b*). Bounding coordinates for all the tiles are provided online by Wolfe (2003*b*). Center point of this tile lies at 56° 10' 12" Lat, -114° 54' Lon. Figure 4-2 illustrates the MODIS tile grid system.

The name of the data set is "MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V004", with a short name of "MOD13Q1". L3 in the dataset name stands for level 3 whereas collection 4 (V004) refers to the reprocessed collection 1 and 3 MODLAND products, sensed from November 2000 to date, applying the latest available version of the science algorithm and using the best calibration and geolocation information available (LDOPE 2002). The filename is in the format; ESDT.AYYYYDDD.hHHvVV.CCC.YYYY DDDHHMMSS.hdf:

Where;

ESDT = Earth Science Data Type name (e.g., MOD13Q1)

YYYYDDD = MODIS acquisition year and Julian day

hHH = horizontal tile number (0-35)

vVV = vertical tile number (0-17)

CCC = collection number

YYYYDDDHHMMSS = processing year, Julian day and GMT time

hdf = suffix denoting HDF file

For example, the file name MOD13Q1.A2004161.h11v03.004.2004186084504.hdf is a MOD13Q1 product, acquired on the 161st day of the year 2004, with 11 as the

horizontal and 3 as vertical tile coordinate (see Figure 4-2), product collection 004, and processed on the 186th day of the year 2004 at the time 8 hr 45 min 04 sec.

The MODIS VI HDF-EOS file provides quality information (Table 4-1) through QA metadata objects (in accompanying metadata files) that summarize tile level quality with several single words and numeric numbers (MLST 2004), thus enhancing the self-describing characteristics of each file and facilitating the archiving and searching of files. They provide the user with general information about the file contents, its characteristics and quality (through the QA) that is used to decide if the file is useful (MLST 2004). Parameter Value Language (PVL) is used to write the various metadata to the product file as: PARAMETER = VALUE. Table B-4 in Appendix B explains the meanings of metadata objects. In addition, the HDF-EOS file also contains two quality SDSs (see Table 4-1) that reflect quality on a pixel-by-pixel basis and thus it is useful for data analyses and application uses of the data (MLST 2004). Both the tile-level and pixel-level quality information are related such that pixel level information is summarized to develop the tile level quality information. The relationship Table B-2 in Appendix B provides VI quality bit combinations and their corresponding metadata objects.

4.2.2 Ancillary data

The ancillary data consists of Millar Western's Forest Products Ltd. Alberta Vegetation Inventory (AVI) and Blue Ridge Lumber Inc. AVI shape files, Environment Canada weather data, and FORWARD weather data. Software packages used to process the data include ERDAS Imagine 8.7, ESRI ARCGIS 8.2, ESRI ARCView, Matlab 6.5, SPSS 12.0 and Microsoft Office XP (Excel, Word, and Visio).

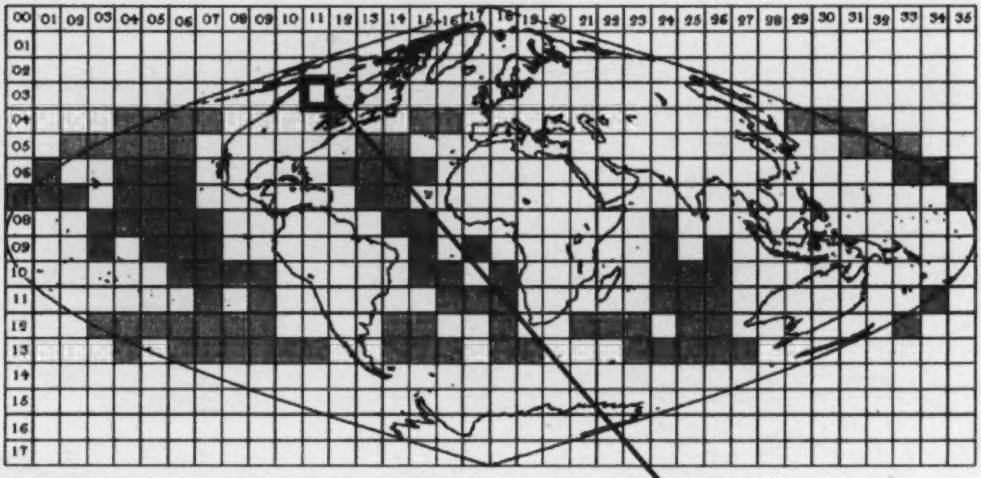

Figure 4-2: MODIS global tile grid. Shaded tiles are the ocean tiles, which are not produced. White tiles are where the land products are generated.

4.3 Image Pre-processing

The pre-processing of the MOD13Q1 dataset has been done by the MODIS Land Science Team (MLST) and includes calibration, geolocation, corrections for molecular scattering, ozone absorption and aerosols, geometric and atmospheric corrections, data quality checks, and temporal compositing. Each of these processes has been discussed at length in the Literature Review-I section.

MODIS products are generated in a hierarchy of levels (Figure 4-3) (LDOPE 2003*a*). Level 0 (L0) refers to the at-sensor recorded "raw" intensities. These intensities are converted into calibrated, geolocated physical units of top-of-atmosphere (TOA) reflectances, which are called Level 1 (L1A and L1B) products. The L1 products are subsequently corrected for atmospheric effects to yield L2 products. Earth-gridded L2 surface reflectance is referred to as L2G surface reflectance. This product is an estimate of at-ground measured reflectances from the TOA measured radiances (to negate the effect of intervening atmosphere) recorded as Digital Counts (DCs) in each pixel of the

satellite image. Surface reflectance product is a key product and serves as an input for all higher level land products (except for land surface temperature).

MOD13Q1 uses MODIS L2G surface reflectances, L2G pointer file, and the L2G geo-angle file as input to the VI equations. The surface reflectances are then temporally composited to generate the 16-day, 250 m VI product. Theoretically, a maximum of 64 observations can be generated by MODIS over a 16-day period because of the sensor orbit overlap and multiple observations in a single day. However, mean global cloud cover of 50-60% restricts this number from 0 to 64 with fewer observations near equatorial latitudes (MLST 2004). The number of acceptable pixels is typically less than 10 and often less than 5 (Huete et al. 2002). The MODIS VI algorithm applies a filter to the available L2 reflectance observations over the 16-day cycle based on quality, cloud and viewing geometry. MODIS, being a "whisk-broom" scanner, causes the pixel size to increase (see Figure 2-3 in Literature Review-I) with scan angle by as much as a factor of 4 (Huete et al. 2002). Therefore, nadir-view pixels possess minimal distortion. Cloud-contaminated and extremely off-nadir pixels are considered low quality while cloud free and nadir-view pixels with minimal residual atmospheric aerosol are considered good quality (van Leeuwen 1999). The VI compositing algorithm consists of three components: BRDF-C: Bidirectional Reflectance Distribution Function Composite, CV-MVC: Constrained-View angle Maximum Value Composite, and MVC: Maximum Value Composite. The number and quality of observations decide which compositing scheme is to be used. The Walthall semi-empirical BRDF model is utilized for the BRDF inversion scheme (Huete et al. 2002).

$$\rho_\lambda(\theta_v, \phi_s, \phi_v) = a_\lambda \theta_v^2 + b_\lambda \theta_v \cos(\phi_v - \phi_s) + c_\lambda \qquad [3]$$

Where;

ρ_λ = atmospherically corrected reflectance in band λ

θ_v = satellite view zenith angle

ϕ_s = satellite view azimuth angle

ϕ_v = solar azimuth angle

a_λ, b_λ, c_λ are the model parameter coefficients (Walthall et al. 1985).

At least five good quality observations are needed to invert the model by a least square procedure. In case where less than five good observations are available, the CV-MVC scheme is used. For a single good observation, VI is computed from this observation. If no good observation is available after the initial data screening, the highest VI value is selected (MVC) regardless of data quality.

Since the FORWARD study area is located at high latitudes, it was anticipated that good quality observations would be available. During the initial processing of MODIS data, the BRDF module was found to be very sensitive to residual cloud cover. Based on reasoning that one contaminated value out of five will significantly bias the nadir-interpolated VI value, the BRDF module was turned off, though it may be reintroduced if the model can be properly adjusted (LDOPE 2004). Figure 4-3 illustrates the flow chart of the start to end processes occurring from the sensor activity to the final MOD 13Q1 product.

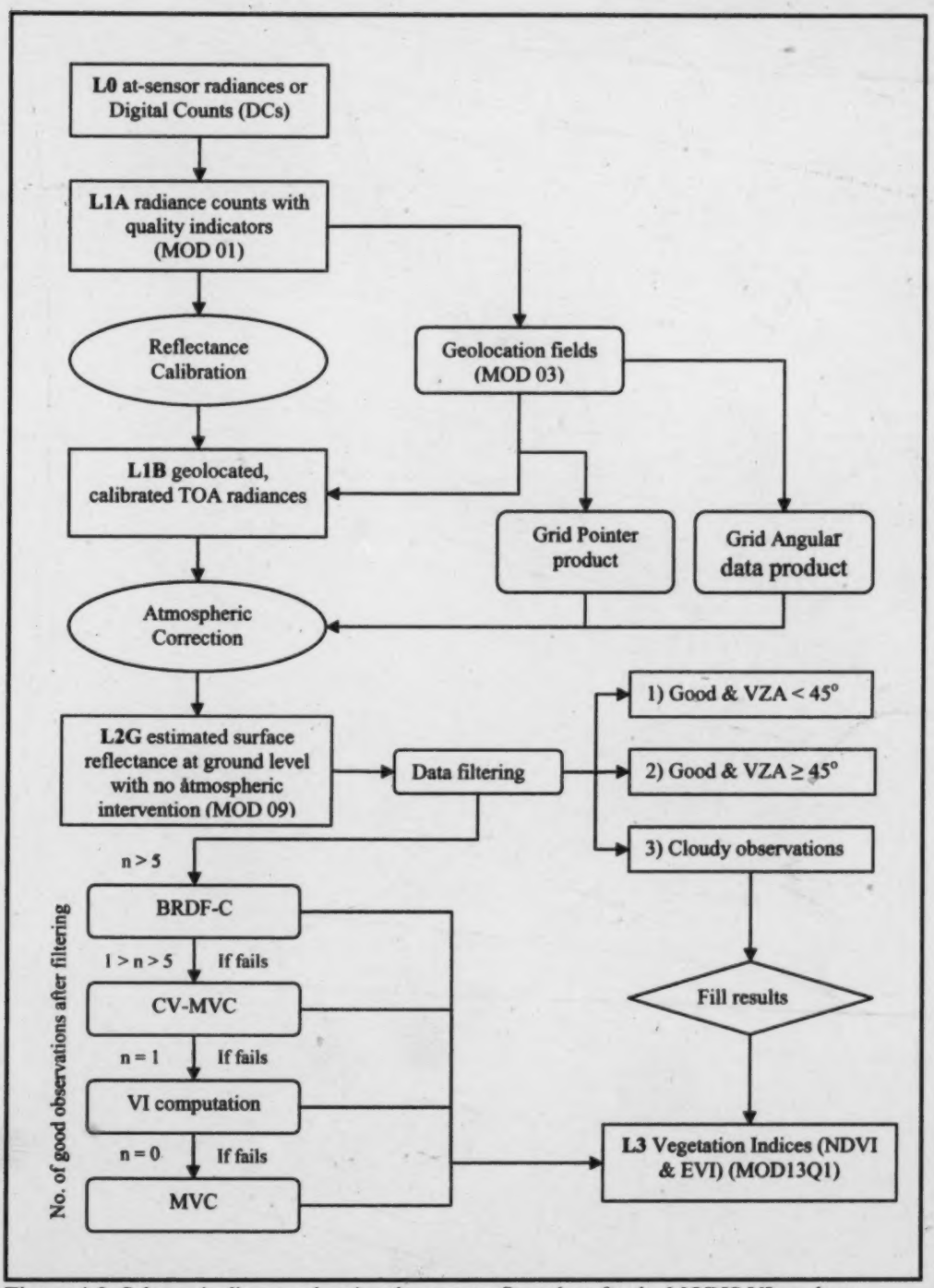

Figure 4-3: Schematic diagram showing the process flow chart for the MODIS VI product.

4.4 Methodology

An automated approach was used to derive the per-pixel VPMs from 4 year (2000-2003) time-series MODIS VI data. Only pixels covering the 16 test FORWARD watersheds were selected for analysis and results are reported as mean of VPMs computed over each watershed for each of the 4 years. Steps undertaken to carry out the analysis are shown in the Figure 4-4 and are explained below.

4.4.1 Data order and download

MODIS VI data (MOD13Q1) was ordered through EOS data gateway interface. The gateway can be accessed using MODIS' website http://modis.gsfc.nasa.gov/ through the "data" link. The Terra MODIS MOD13Q1 dataset was chosen in the search criteria and the coordinates of the study area were fed into the system. The search criteria retrieved the VI datasets from the years 2000 to early 2004. Data for 2004 has not been used in this study. 20 EOS-HDF files for year 2000 and 23 files for each year, 2001, 2002 and 2003, (total of 89 files with 89 metadata files) were ftp-pulled from NASA's server.

4.4.2 Data quality check

Once downloaded, data was checked for quality by metadata check, usefulness index check, and an online quality information check.

4.4.2.1 Metadata check

The accompanying metadata files were analyzed for quality control. For this purpose 'read_meta' algorithm was downloaded from the MODIS LDOPE tools distribution site (http://lpdaac.usgs.gov/landdaac/tools/ldope/index. asp) and installed on the computer. The program reads a set of specified metadata from MODIS Land HDF-EOS data product and writes the output to standard output. If no options are specified, all metadata are read (Land Processes Distributed Active Archive Center (LP DAAC) 2004). The program was run in the Microsoft Disk Operating System (MS DOS) environment to extract metadata objects of significance from the 89 metadata files. Each file has 18 metadata objects, the first 6 of which are called "QAFlags" and include Automatic quality flag, Operational quality flag, Science quality flag, and their explanations (see

Appendix B). The output was imported to MS Excel software and results are presented below. The command used to extract metadata is provided in Appendix A.

Another algorithm, 'unpack_sds_bits', was also downloaded from the MODIS LDOPE tools distribution site and used to decode the requested bit fields. The program writes to an output HDF file. The output SDS data type is uint8, uint16 or uint32 depending on the number of unpacked bits (LP DAAC 2004). The command was executed in the DOS environment and is provided in Appendix A. The problem encountered with this tool was that output file format was HDF and not EOS-HDF, which resulted in loss of the projection information of the tile. Re-projection of the tile to SIN grid involves a re-sampling procedure which will translate to the loss of some VI information in the tile. Therefore, the results of this algorithm were not used in the subsequent analysis.

Automatic quality flag for the seven images in year 2000 i.e. from February 18 2000 to May 24 2000 was set to "suspect" while the rest of the 82 images had a "passed" status. This flag is the result of an automatic quality assessment performed during product generation. The flag is set to "passed" if QAPercentMissingData < 5%; set to "suspect" if QAPercentMissingData > 5% or < 50%; and set to "failed" if QAPercentMissingData > 50%, where the "QAPercentMissingData" is also a QA metadata object and is described in Appendix B.

The Operational quality flag, which indicates if the data are corrupted in the transfer, archival, and retrieval processes, was set to "passed". The Science quality flag, which indicates manual, science-QA performed by VI Science Computing Facility (SCF) personnel (MLST 2004), was set to "being investigated" for collection 4 VI data. Currently the Science quality metadata are not being updated in the metadata files and so the values must be checked online at the LDOPE (2003*b*) website. The percent interpolated data, missing data, out-of-bound data, not-produced-due-to-other-reasons data and not-produced-due-to-cloud data were zero. All data were sea processed and tiles consisted of 100% land pixels.

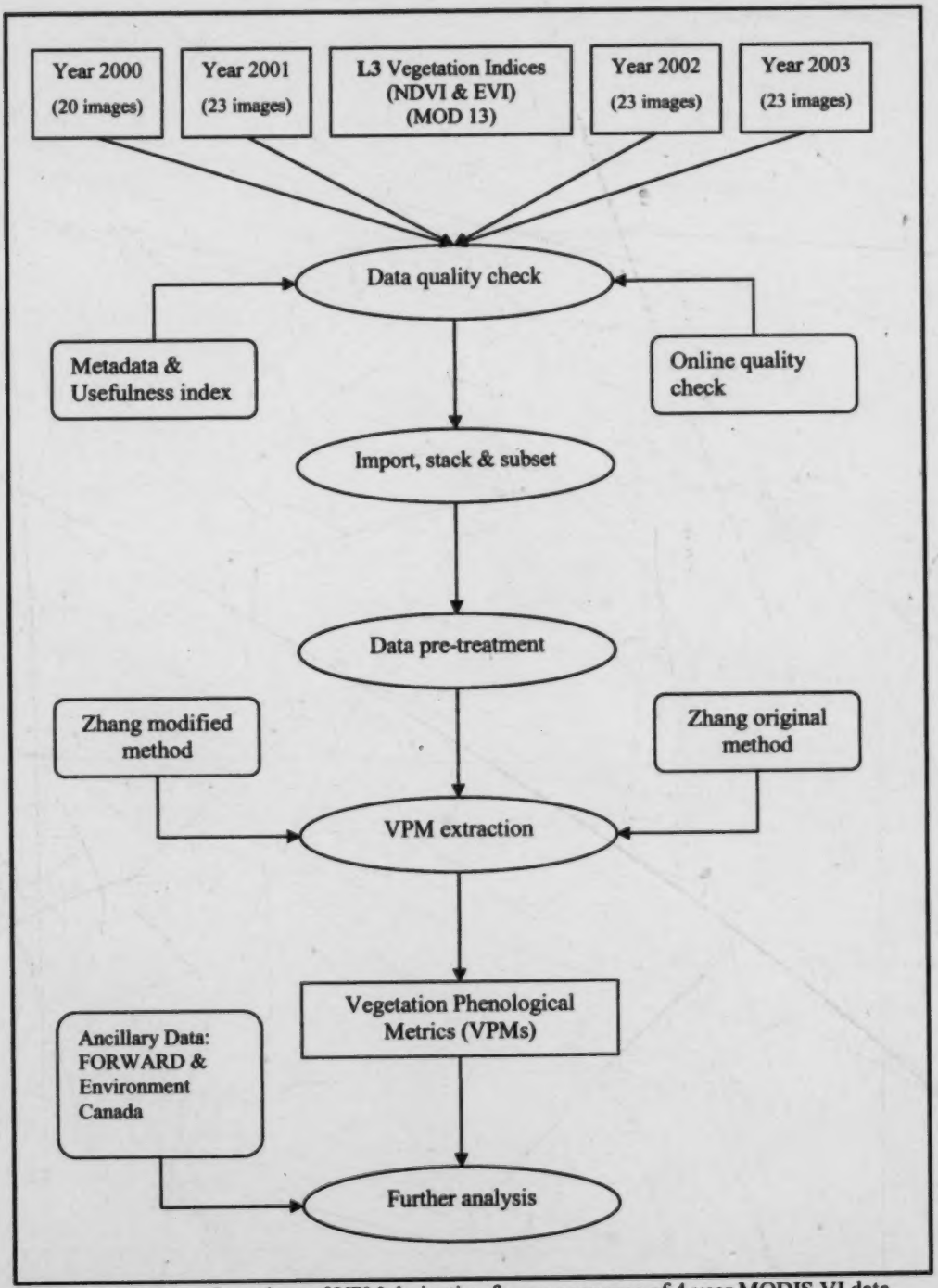

Figure 4-4: Process flow chart of VPM derivation from a sequence of 4 year MODIS VI data.

Figure 4-5 and 4-6 illustrate percent good quality pixels and percent cloud cover, respectively, in the 89 acquired image tiles for the year 2000-2003. Five images were found to have less than 60% (arbitrary set threshold) good quality pixels, i.e. the image tiles created on June 10 2001, October 16 2002, November 1 2002, October 16 2003, and November 1 2003 had 34%, 43%, 54%, 52%, and 53% good quality pixels, respectively. Four images were found to have greater than the acceptable standard of 10% cloud cover i.e. the image tiles created on June 10 2001, October 16 2001, March 22 2002, and December 3 2002 had 23%, 11%, 14%, and 14% cloud cover, respectively. In addition, data was also checked for the Product Generation Executive (PGE) version, which consists of one or more science code executables, control scripts and support files. It is a three digits number, the first one is unique to the product collection (since the data is collection 4 so the number starts from 4), the second reflects a major science code change such as an algorithm change, and the third represent a minor code change such as bug fixes etc (LDOPE 2003*c*). Figure 4-7 suggests that there were no major science code changes in the VI algorithm since the year 2000.

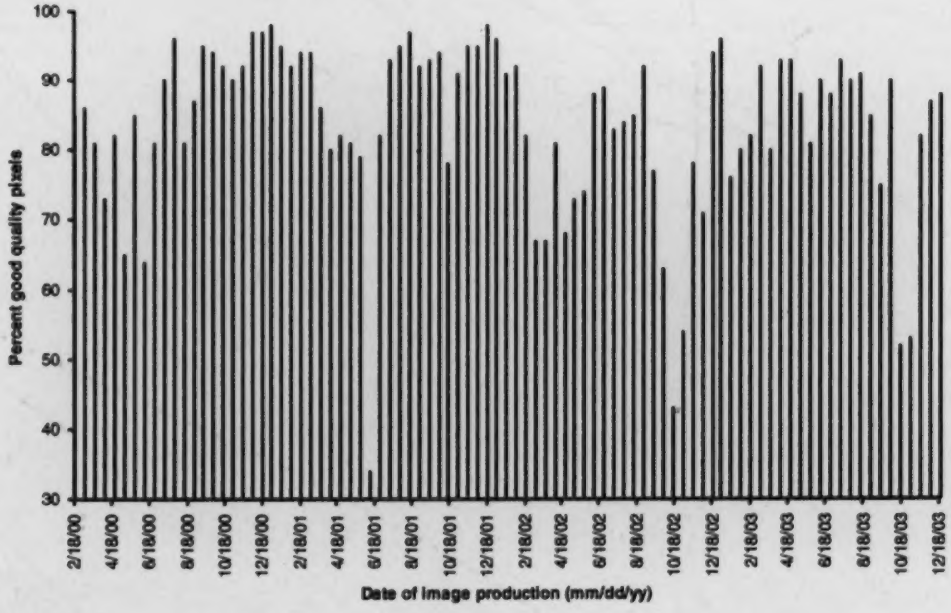

Figure 4-5: Percent good quality pixels in tiles of 89 images for the year 2000-2003.

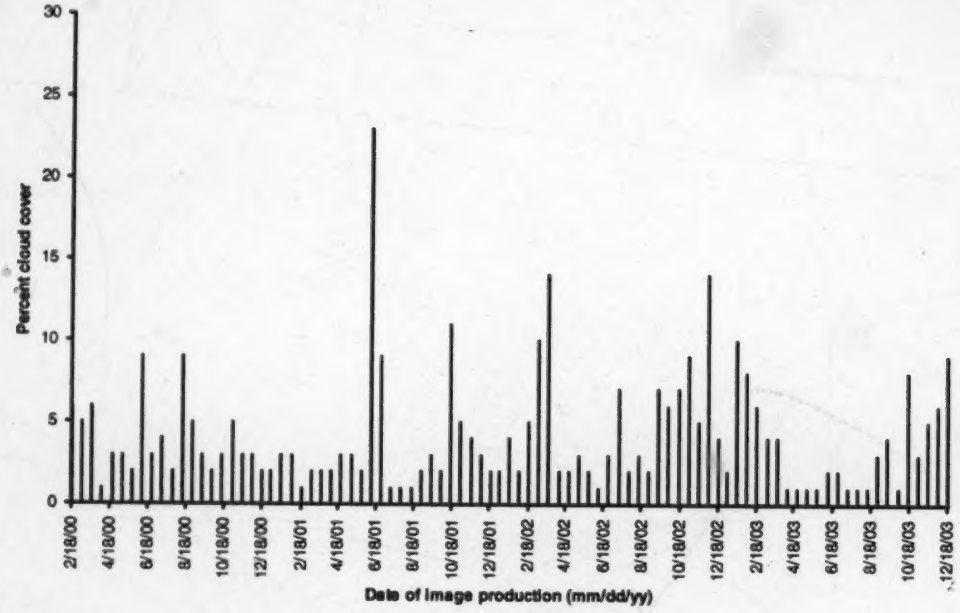

Figure 4-6: Percent cloud cover over tiles for 89 images for the year 2000-2003.

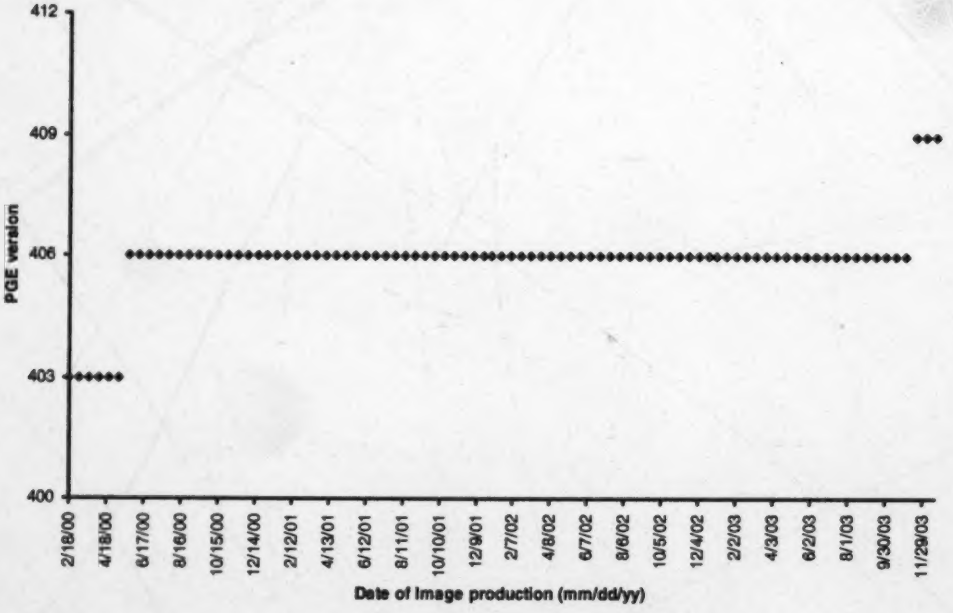

Figure 4-7: Product version history of 89 images for the year 2000-2003.

4.4.2.2 Usefulness index check

Usefulness index is the 2nd bit-field in QA SDS and a superior quality indicator. Its value for a pixel reflects the variable conditions of aerosol quantity, atmospheric correction, cloud cover, shadow, and sun-target-viewing geometry. A specific score is assigned to each condition and the sum of all the scores gives a usefulness index value for the pixel. Table B-3 in Appendix B provides the usefulness index scaling method.

The metadata objects QAPERCENTPOORQ250M16DAYNDVI and QAPERCE NTPOORQ250M16DAYEVI are computed as sums of the NDVI and EVI usefulness indices and indicate, respectively, the percent frequency distributions of the NDVI and EVI quality (MLST 2004). Their values reflect 16 quality levels from 'perfect' (highest) to 'not useful' (lowest) in the descending order from left to right. Figure 4-8, 4-9, 4-10 and 4-11 present the frequency distribution of EVI and NDVI quality over the image tiles for the year 2000, 2001, 2002 and 2003, respectively. There are no "perfect" or "high" quality pixels (first two levels) but the majority of the pixels are "good" quality from April till November of each year. The start and the end of the year, however, are dominated by "acceptable" quality pixels. Since this study will utilize pixels from the growing season of vegetation, the pixels employed are "good" quality for EVI and NDVI. Moreover, FORWARD watersheds are located near the center of the MODIS scan tile, which translates to smaller zenith and scan angles. This reduces the risk of faulty VI pixel values due to larger scan angle. For instance, a high view angle would explain the high EVI value. Sun angles were visually inspected to check for any unusual VPM behavior and majority of the angles were found to be in acceptable range.

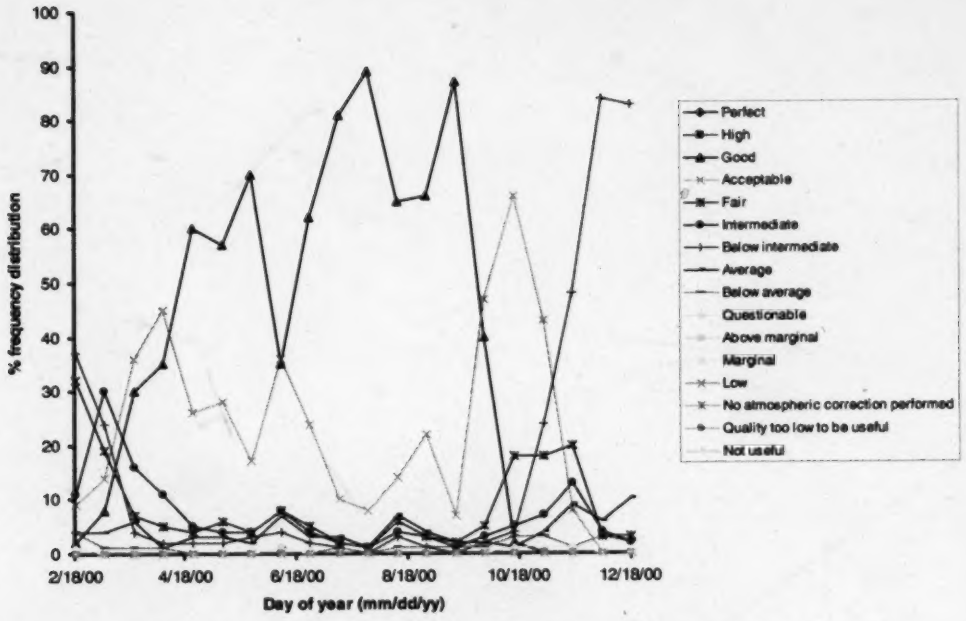

Figure 4-8: Frequency distribution of EVI and NDVI quality for the year 2000.

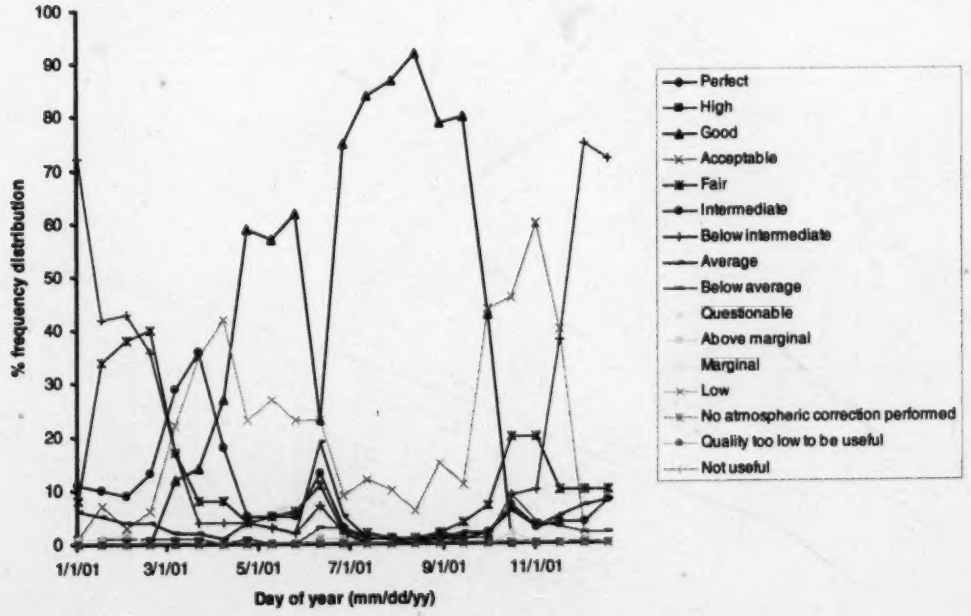

Figure 4-9: Frequency distribution of EVI and NDVI quality for the year 2001.

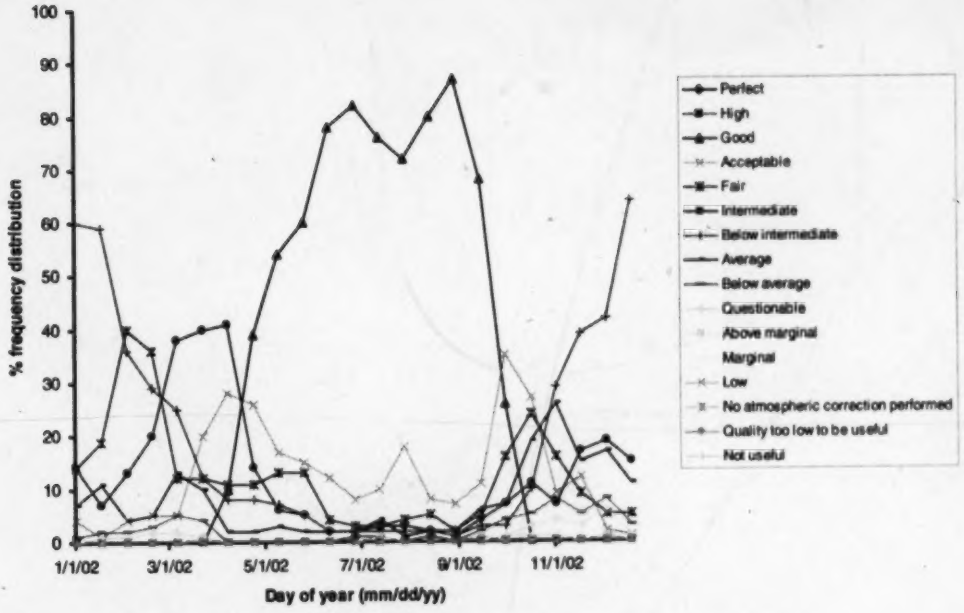

Figure 4-10: Frequency distribution of EVI and NDVI quality for the year 2002.

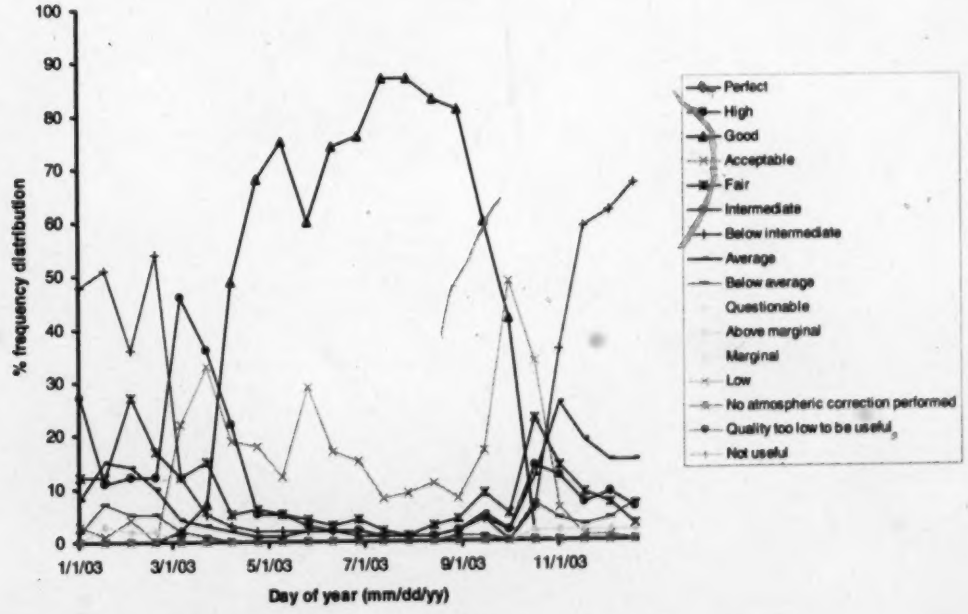

Figure 4-11: Frequency distribution of EVI and NDVI quality for the year 2003.

4.4.2.3 Known product issues website (LDOPE 2004)

The following issues identified by LDOPE (2004) with VI data were taken into consideration:

1) Beginning with Julian day 257, 2000 only the CV-MVC method is used due to complications with the BRDF method.

2) The 16 day compositing periods for the MOD13Q1 VI product are aligned with January 1, which translates to 22.8 (365/16 = 22.8) compositing periods in a year. The end-of-year shortened compositing period (0.8 x 16 = 12 days) is supplemented with data from the beginning of the subsequent year, while maintaining alignment with January 1. This results in a data overlap between end-of-year and beginning-of-year compositing periods.

3) Double line artifact were seen in collection 4 of MOD13 VI data on data Julian day 170 2002 and 219 2002 over western Canada due to a geolocation problem caused by an orbit drag makeup maneuver performed on the same dates (see Figure 4-12).

4) Stripping was observed in some of the MOD13 VI data due to an aerosol retrieval problem related to band 7 stripping in the MOD09 reflectance product (see Figure 4-12).

5) Blocky EVI and NDVI retrieval was observed due to the presence of high aerosol in daily surface reflectance products (MOD09) causing the algorithm to use data from different days than the one used for the neighboring pixels (see Figure 4-12).

6) Prior to data Julian day 017, 2001 and PGE versions 2.3.1, unrealistically high EVI values over snow, ice and clouds were observed. However, an update to the EVI algorithm has rectified the problem and since the PGE version of collection 4 data (used for this study) is 4.0.3 and above. This is a not a concern here.

Figure 4-12: Three images showing artifacts such as double line (left), stripping (center), and blockiness (right). The images are ndvi.MOD13Q1.A2002161.h09v05.004.2003241004232 (left), ndvi.MOD13A1.A2003257.h11v09.004.2003285030319 (center), ndvi.MOD13Q1.A2003081.h21v06.004.2003110132223 (right).

4.4.2.4 Data quality conclusions

As a result of metadata, usefulness index and online quality check, it was concluded that the data must be pre-treated to extract VPMs. Neither any data was screened nor was any of 89 layers rejected on the basis of data quality check as no appropriate criteria/threshold value could be developed. In addition, the metadata objects reflected the averaged conditions of all pixels in the tile, which may not be the representative of the FORWARD Area of Interest (AOI) pixels since FORWARD watershed (study AOI) pixels constitute only 0.05% of the whole tile pixels (see Table 4-3). Metadata analysis was based on the assumption that the error distribution is uniform throughout the tile area e.g. cloud cover of 23% doesn't necessarily imply that it is 23% over the FORWARD study area, though it was assumed so. It may be less or more than that. The better approach is to derive AOI specific metadata but, this is thought to be out of scope for this research work. Nevertheless, the tile-level data quality check combined with the online check provided a good idea of data issues.

4.4.3 Data import, stack and subset

After quality checks, 89 MOD13Q1 files were imported into ERDAS Imagine GIS software. All the 11 SDSs in each HDF-EOS file were converted to 11 image (.img) files, the ERDAS Imagine standard raster file format. EVI images for each year were then stacked using the "Image Stack" module and subsetted using the AOI shape file of the watersheds. The same procedure was repeated for each SDS.

4.4.4 Data pre-treatment

Time-series VI data comprised of 23 16-day composite VI images for each year, from 2000 to 2003. Per-pixel VPM extraction required pre-treatment of this data. For this purpose the stacked-subsetted VI data were exported as Binary Interleaved (.bil) files to Matlab and treated using Wardlow et al. (2004) method. Based on the reasoning that it is very unlikely for the onset of greenup to occur before March 21 and the end of greenup to occur after November 17 for this study area, time-series VI data were divided into two parts and treated differently; as follows:

4.4.4.1 Tail treatment

Eight composite periods from 1 to 5 and 21 to 23 were designated as time-series tail. First five composite periods 1 to 5 spanning January 1 to March 21 of each year were designated as front tail, while the last three, 21 to 23 spanning November 17 to December 31 were designated as end tail. Tails were vigorously smoothed, since the extraction of phenological metrics was concerned only with the vegetation growth period and thus, variation occurring in these segments was deemed as of little to no use (regardless of its source) in the determination of onset dates for vegetation in the Boreal plain ecozone. An extremely conservative latent (or background) VI threshold of 0.15, which was determined by visual inspection of pixel-level time series plots, was used to screen tail pixels with anomalous values suppressed due to pre-processing artifacts (clouds, aerosols, signal noise etc.). It was anticipated that eliminating the temporal data variability induced by these sub-background VI values should theoretically do no harm to the analysis (Kastens 2004, Verbal communication).

Front and end tail data was subjected to flat smoothing and values were replaced by the median computed over the first five VI values (for front tail) and last three VI values (for end tail).

4.4.4.2 Interior treatment

15 composite periods from 6 to 20 spanning March 22-November 16 were designated as time series interior. For the interior treatment, all the local minima VI values, xi (where i represents the time period) were identified such as $xi-1 > xi < xi+1$.

The minima are points where the value of the function is less than both the adjacent predecessor (xi-1) and successor (xi+1) points. The interior minima VI values were replaced with the minimum value of x_{i-1} or x_{i+1}. This treatment, however, had no impact on the valid peak and increasing or decreasing interior VI values. The VI peaks were considered valid because CV-MVC instead of MVC was used to generate the VI values, and it does not select maximum VI values. Though the interior treatment may have replaced some legitimate VI values, identifying the onset of greenup was primarily dependent on the initial monotonic greenup segment of each VI curve, which, theoretically, should have had no substantial legitimate VI minima values (Wardlow et al. 2004). The true end-of-segment VI minima values, however, were negatively impacted by the treatment. This had negligible impact on the subsequent VPM extraction (Kastens 2004, Verbal communication). Figure 4-13 and 4-14 illustrate the results of data treatment of the mean EVI and NDVI computed over 16 watersheds, respectively, while Figures 4-15 and 4-16 illustrate the results for the mean EVI and NDVI computed over the Sak A watershed, respectively.

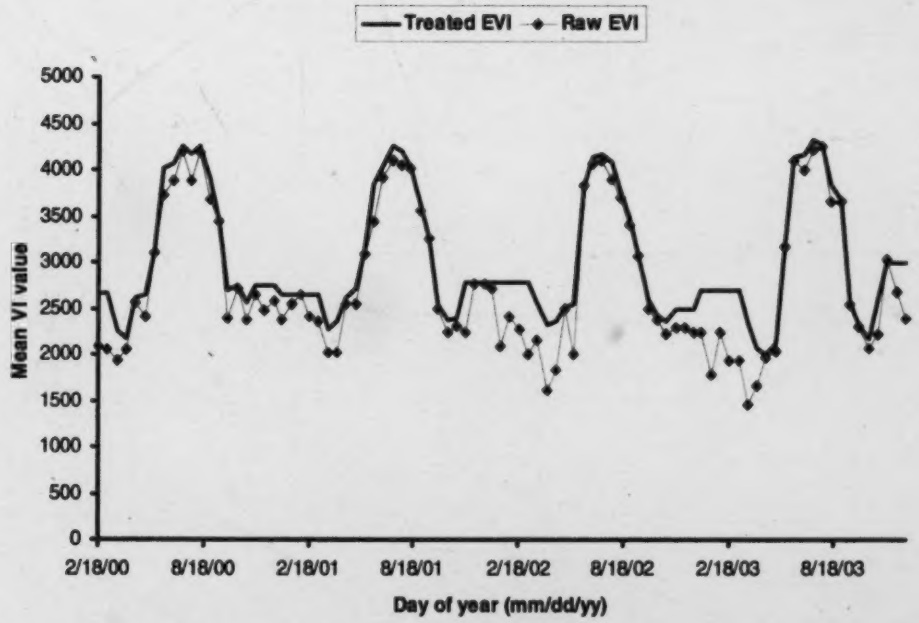

Figure 4-13: Comparison of before versus after treatment for mean EVI over 16 watersheds.

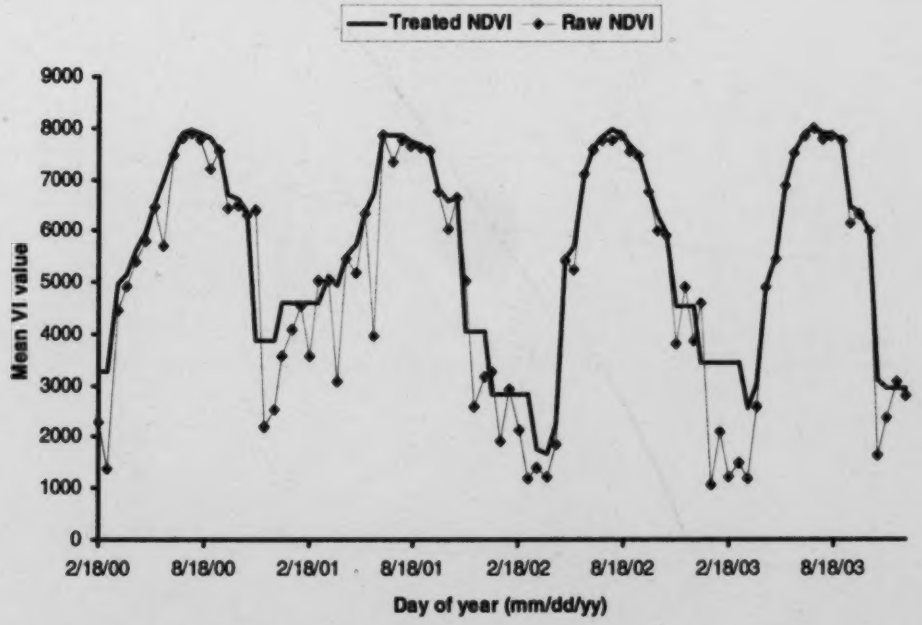

Figure 4-14: Comparison of before versus after treatment for mean NDVI over 16 watersheds.

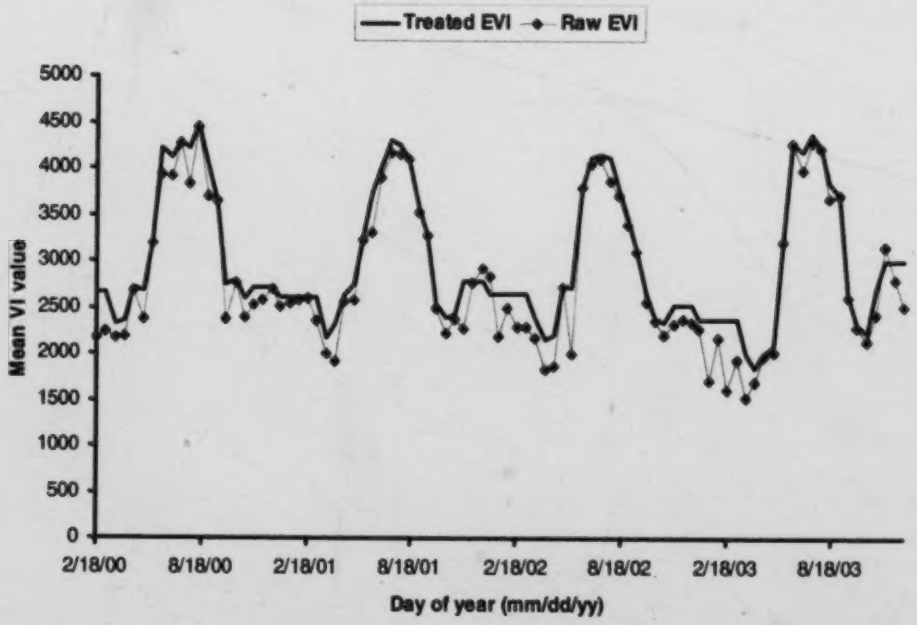

Figure 4-15: Comparison of before versus after treatment for mean EVI over Sak A watershed.

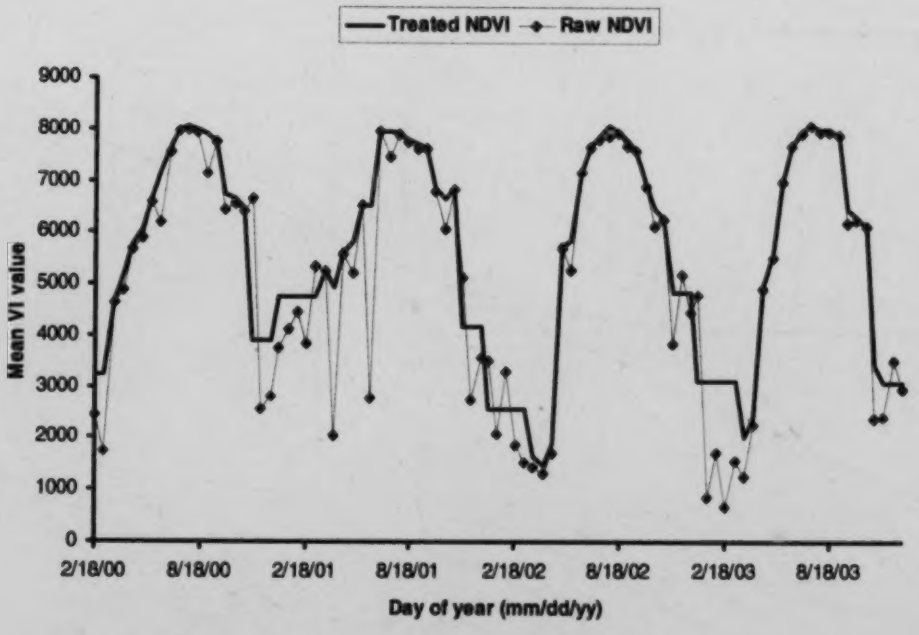

Figure 4-16: Comparison of before versus after treatment for mean NDVI over Sak A watershed.

4.4.5 Extraction of Vegetation Phenological Metrics (VPMs)

A total of 10 VPMs were derived from the MODIS 4 year (2000-2003) pre-processed, pre-treated VI data versus time curve. These VPMs are adapted from the phenological parameters of Reed et al. (1994), Lloyd (1990) and Malingreau (1986). A typical forest phenological cycle has the same basic elements: from null in winter (or low) to full photosynthetic status in late spring and back to senescent in the fall as shown in Figure 4-17 and different species vary in phase and intensity of the peak. VPMs are aimed at characterizing and capturing this variation in each year's seasonality of the time series data. Table 4-2 provides the VPMs and their phenological interpretations and Figure 4-17 provides a further understanding of VPMs.

Table 4-2: Vegetation Phenological Metrics (VPMs) and their descriptions.

Metrics	Description of metrics
Onset of Greenup (OG)	Beginning date of photosynthetic activity that corresponds to the start of growth development which begins as soon as climate conditions are favorable. This is the x-axis value at the first point of inflection of the time series VI curve
Onset VI value	Level of photosynthetic activity at which the onset occurred. This is the y-axis value at the first point of inflection of the time series VI curve
Peak date	Date of maximum photosynthetic activity. This is the x-axis value at the peak of the time series VI curve
Peak VI value	Maximum level of photosynthetic activity. This is the y-axis value at peak of the time series VI curve
End of Greenup (EG)	End date of the photosynthetic activity or dormancy, which is a state of suspended growth and metabolism. This is the x-axis value at the second point of inflection of the time series VI curve
End VI value	Level of photosynthetic activity at which the end of greenup occurred. This is the y-axis value at the second point of inflection of the time series VI curve
Length of growing season	Duration of photosynthetic activity. This is the linear distance between the two points of inflection parallel to the x-axis
Time integrated VI value	Net primary production and the accumulation of biomass over the growing season. This is the area under the curve
Rate of greenup	Acceleration of photosynthetic activity. This corresponds to the positive slope of the curve (dx/dt)
Rate of senescence	Deceleration of photosynthetic activity. This corresponds to the negative slope of the curve (-dx/dt)

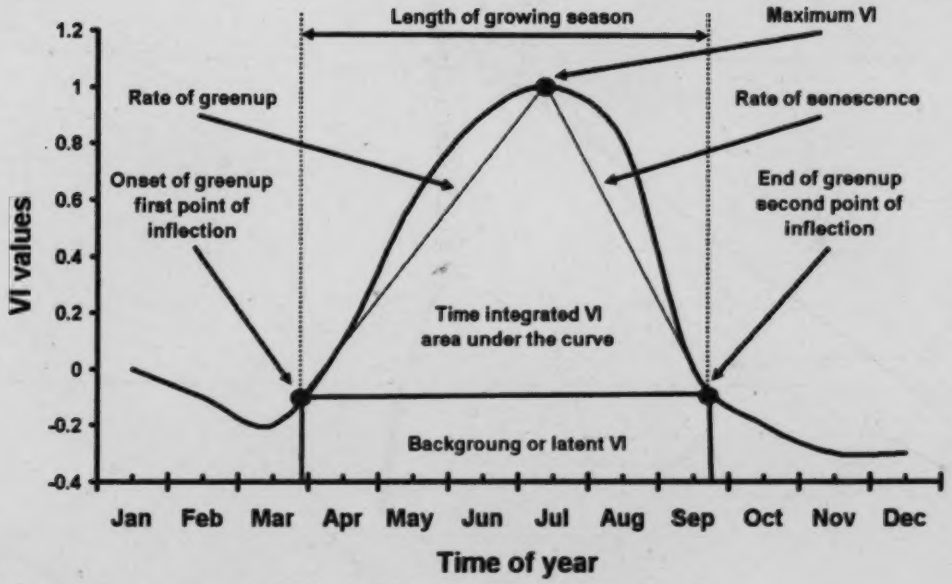

Figure 4-17: Derivation of VPMs from the yearly VI temporal profile.

Past efforts using time-series VI data to identify key phenological transition dates: onset of greenup (OG) and end of greenup (EG) are summarized in Literature Review-II section. The approaches adopted in this study to extract OG from the VI time series curve are the Zhang approach and the Zhang modified approach. Zhang approach identifies the extreme points where rate of change in curvature of the fitted logistic models to the VI time-series data, changes sign as the phenological transition dates (OG and EG). This method uses the function of the form as given by Zhang et al. (2003):

$$y(t) = \frac{c}{1+e^{a+bt}} + d \qquad [4]$$

Curvature, K at any time t can be computed using:

$$K = \frac{d\alpha}{ds} = -\frac{b^2 cz(1-z)(1+z)^3}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{3}{2}}} \qquad [5]$$

The rate of change of curvature, K', is then:

$$K' = b^3 cz\left\{\frac{3z(1-z)(1+z)^3\left[2(1+z)^3 + b^2c^2z\right]}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{5}{2}}} - \frac{(1+z)^2\left(1+2z-5z^2\right)}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{3}{2}}}\right\} \quad [6]$$

Where;

t = time in days

y(t) = VI value at time t

a and b = fitting parameters

$c + d$ = maximum VI value

d = background or latent VI value

$z = e^{a+bt}$

α = the angle in radians of the unit tangent vector at time t along a differentiable curve

s = unit length of the curve

The modified approach goes a step further by computing another point of maximum second derivative of the fitted logistic function and identifies the transition dates as the average of the two points.

Once the OG was identified using both approaches, the EG was extracted using a similar method as for the OG but the data was treated in reverse chronological sequence. Data were assumed to have one mode (i.e. one growth cycle), with OG being determined by moving inward from the beginning of the year and the EG determined by moving inward from the end of the year. Since the MODIS dataset for the year 2000 is not complete (data is generated from February 18 and not from January 1 as with the years 2001, 2002 and 2003), the "date" metrics (i.e. OG date, EG date, and maximum VI date) from 2000 were scaled as if the 2000 data had a complete stack with 23 layers instead of 20. This allowed data from the year 2000 to be compared directly with values from other years. The date metrics were snapped to 16-day MODIS composite periods, i.e. the 'composite periods' were used as the time/date measuring units. For example, a pixel having an OG date value of 8 means that onset occurred during period 8 of 16-day raw imagery collection time frame. Values less than zero were replaced with zero and all zero

values were deemed as either background, non-vegetated, or problem pixels for which no metrics were computed. Other VPMs were calculated only when the OG and EG dates were both defined, and in this case only when the EG date occurred more than one period after the OG date.

The Zhang algorithm, through use of a continuous, best-fit function, allows one to speculate OG down to as much temporal detail as desired (down to fractions of a second and beyond, as far as machine precision permits). Though, it is easy to argue either way regarding the significance of estimating onset beyond the 16-day resolution of the data, it really depends on how the information is being used. In this study, the OG and EG metrics were calculated down to the day (daily OG and EG), in addition to down to the 16-day composite period. However, this "drilling down" luxury could not be afforded with other VPMs such as with the "maximum VI date" VPM, as this was derived directly from the VI time series. Maximum VI date was measured instead in composite periods and reported in days using the relation that 1 composite period = 16 days. While the OG and OE VI values could also not be calculated down to the day, these VPMs can be interpolated to arrive at daily values.

Finally, the length of the growing season, measured in composite periods and reported in days, was computed by subtracting the daily OG date from the daily EG date (length of growing season = daily OG date – daily EG date + 1). The rates of greenup and senescence, measured in VI units/composite period, were computed as straight line slopes (dx/dt) from the OG to maximum VI and maximum VI to EG point (see Figure 4-17), respectively.

4.4.6 Further analysis

Once the metrics were computed for each pixel in the study area, tables of results were generated from the VPM images and are presented in the next chapter. This involved computing the mean and standard deviation of VPMs over each watershed. The sample size is variable since the watersheds' sizes and the number of pixels comprising each is variable. Table 4-3 presents the number of 250 x 250 m (0.0625 km^2 area) pixels covering each watershed. As a result of variable scan angles and image compositing, the final MODIS VI pixel resolution comes out to be 231 x 231 m (0.0534 km^2). Based on

this resolution, the total number of pixels covering the FORWARD study area will slightly increase to 13861 from 11836 (see Table 4-3). Table 4-3 gives an idea of how many pixels were used to compute the mean of VPMs over each watershed. The general trend observed during any image analysis exercise is that statistical means computed over larger pixel samples tend to reduce random errors. This implies that smaller watershed VPMs are more vulnerable to errors propagation since a small number of pixels have been used to compute means, and one or two anomalous values can significantly bias the statistic. In the next step, results were subjected to such statistical procedures as ANOVA, the Pearson correlation coefficient computation and Multiple Comparison Tests (MCTs) to derive meaningful conclusions.

Table 4-3: Area and number of pixels for each watershed.

Watersheds	Area (km^2)	No. of pixels (250 x 250m)	No. of pixels (231 x 231m)
Goose	150.57	2410	2822
Sak A	233.93	3743	4384
Chickadee	155.19	2483	2908
Two Creek	129.39	2070	2425
Burnt Pine	7.66	123	143
Fireweed	5.69	91	107
1A	5.10	82	96
Cassidy	5.87	94	110
Kashka	3.91	63	73
Millions	2.43	39	45
Mosquito	3.07	49	57
Pierre	2.58	41	48
Sak B	7.04	113	132
Thistle	9.01	144	169
Toby	2.63	42	49
Willow	15.57	249	292
All area	739.65	11836	13861

Chapter 5

Results and Discussion

A suite of 10 per-pixel VPMs, using both Zhang and Zhang modified approaches, was developed using 4 year time-series MODIS VI data. The analysis was carried over for each pixel (a total of 11836) in the16 FORWARD test watersheds, but for the ease of presentation and further analysis as well as making generalizations, measure of central tendency and dispersion of the VPMs were computed over each watershed. The statistical mean of VPMs computed for the vegetated pixels in each of the 16 watersheds based on four comparative approaches is given in Table 5-1 to 5-4; the standard deviation is presented in Appendix C as Table C-1 to C-4 for the years 2000 to 2003. The OG and EG dates are measured on a daily basis and reported in calendar date units. Composite periods were used as the units of measurement for the peak VI date and length of growing season metrics; they are translated into units of calendar dates and number of days, respectively, for ease of presentation. VI value metrics (OG VI, EG VI and peak VI value) and time integrated VI value are presented in the same units as were measured; VI units, which vary from 0 to 1 in the treated data (and -0.2 to 1 in the data before treatment) are scaled up by a factor of 10,000. The rates of greenup and senescence metrics are measured and reported in the VI units per composite period multiplied by 10,000. Because of the tail treatment, no OG dates could appear before composite period 6 (March 21) and no EG dates could occur after composite period 20 (November 17) for all of the four approaches.

For discussion purposes, VPMs derived from EVI and Zhang method are represented by EVIz, EVI and Zhang modified method by EVIm, NDVI and Zhang method by NDVIz, and NDVI and Zhang modified method by NDVIm (see Figure 5-1). These four comparative approaches to derive four sets of VPMs were statistically analyzed to check for differences among the four approaches.

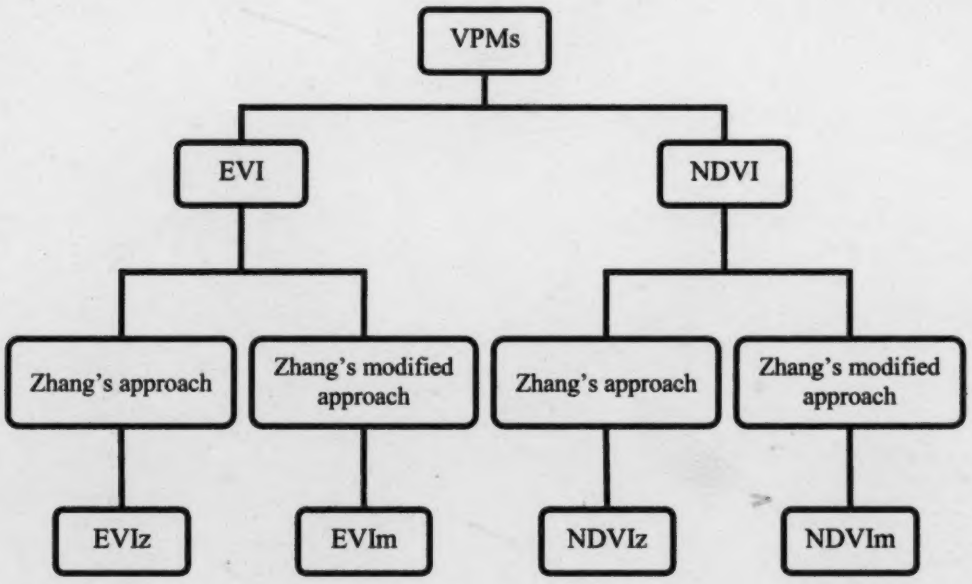

Figure 5-1: Four comparative approaches to derive VPMs.

Mean VPMs shown in Table 5-1 to 5-4 were first yearly stratified and the averages and variances were then determined for the resulting sample size of 16 observations (one for each watershed) for each of the 10 VPMs in each year 2000, 2001, 2002 and 2003. ANOVA at alpha level 0.05 revealed that the differences in average values (computed for N = 16) for each of the VPMs among the four methods are highly significant ($P < 0.001$) as shown in Table 5-5. The Levene statistic, used as a test of homogeneity of variances, confirmed that all the methods have equal variances and thus verified the assumptions of ANOVA. Tukey HSD and Bonferroni Multiple Comparison Tests (MCTs) were applied to compare each method with the other and both of the tests yielded the same results. Homogenous subsets of VPMs based on Tukey HSD MCT were established and given in Table 5-6.

Table 5-1: Mean of EVIz based VPMs for 2000-2003 for 16 watersheds.

Watersheds	Year	Onset date[1]	End date[1]	Peak date[1]	Onset value[2]	End value[2]	Peak value[2]	Length[3]	Time-int.VI[2]	Rt of green up[4]	Rt of sense-cence[4]
1A	2000	5/27	9/12	7/20	2932	3355	5734	109	39834	913	714
	2001	5/8	9/21	8/6	3030	2918	4528	137	40952	346	411
	2002	4/30	9/23	7/4	2987	2848	5039	147	43252	628	361
	2003	5/25	8/31	7/5	2526	2974	5103	98	35909	1051	483
Burnt pine	2000	5/26	10/10	7/24	3122	2985	6030	138	50005	920	583
	2001	5/10	10/3	7/26	2670	2779	5237	147	46191	643	490
	2002	5/3	10/2	7/18	3041	3063	5159	153	47254	619	395
	2003	5/6	9/13	6/29	2471	2814	5557	131	41961	1143	476
Cassidy	2000	5/9	9/21	7/20	2956	3596	6034	135	48012	764	532
	2001	5/24	9/15	7/12	3279	3110	5997	115	41261	1052	664
	2002	4/16	10/8	7/5	3459	2803	5467	176	51169	690	418
	2003	5/11	9/7	7/19	2691	2858	5396	120	40926	687	606
Chickadee	2000	5/16	9/23	7/20	2760	3009	5299	130	42171	723	505
	2001	5/21	9/21	7/10	3060	2814	5348	124	40156	838	471
	2002	5/4	9/28	7/8	2774	2632	4985	148	42052	757	409
	2003	5/5	9/8	7/18	2543	2698	4901	127	38290	644	555
Fireweed	2000	6/9	9/22	8/12	2540	2596	4566	106	31367	562	600
	2001	5/5	9/17	7/24	2477	2525	4987	136	36826	725	577
	2002	4/30	9/25	7/22	2268	2367	4397	149	34969	709	430
	2003	4/30	9/13	7/23	1720	2548	4557	137	33606	600	528
Goose	2000	6/11	9/14	8/1	2357	2593	4409	96	31693	628	474
	2001	5/8	9/20	7/31	2300	2385	4443	136	33822	504	503
	2002	5/7	9/14	7/17	2356	2431	4388	130	32202	741	439
	2003	5/3	9/19	7/27	2037	2296	4352	139	32198	583	525
Kashka	2000	5/13	9/18	7/27	2461	2784	4303	129	34728	438	384
	2001	5/10	9/12	7/9	2744	2476	4705	126	35117	659	463
	2002	4/30	8/19	7/5	2488	2680	4255	112	33633	530	360
	2003	4/24	9/2	7/12	2538	2444	4564	132	32820	748	479
Millions	2000	5/7	9/5	7/10	3032	3508	4807	122	36575	596	414
	2001	5/22	8/19	6/27	3372	3214	4878	91	31937	685	449
	2002	5/2	8/24	6/6	3368	3178	4745	115	35238	731	260
	2003	4/29	8/21	6/30	3188	2949	4369	114	34084	583	330
Mosquito	2000	5/16	10/4	7/11	2660	2791	5457	143	43757	817	462
	2001	5/24	9/27	7/1	2701	2440	5457	127	39787	1067	496
	2002	4/15	10/5	6/21	2800	2554	5028	174	43385	834	361
	2003	5/9	9/12	7/19	2315	2393	4981	127	36747	743	637
Pierre	2000	5/31	9/14	8/3	2639	3018	4563	107	33353	528	512
	2001	5/21	9/25	8/2	3286	2685	4538	128	32654	514	490
	2002	5/12	10/4	7/22	2905	2635	4400	146	35786	604	376
	2003	5/1	9/13	7/16	2516	2837	4831	136	36945	608	604
Sak A	2000	5/27	9/29	7/28	2836	2874	5225	126	41041	709	546
	2001	5/12	9/23	7/26	2715	2663	4845	134	39245	562	478
	2002	4/28	9/27	7/12	2668	2599	4905	153	42046	669	426
	2003	5/11	9/9	7/13	2329	2658	4910	123	36683	800	504
Sak B	2000	5/5	10/10	8/6	2208	2740	5642	160	48320	644	615

	2001	5/15	10/9	7/15	2430	2718	5810	147	45503	972	538
	2002	5/9	10/5	7/20	2218	2573	4985	150	40228	804	427
	2003	4/24	9/30	7/28	1682	2303	5159	160	39024	720	663
Thistle	2000	5/20	9/8	7/16	2942	3054	4937	112	36097	672	544
	2001	5/22	9/5	7/12	3069	2767	4820	108	35987	606	457
	2002	5/1	9/18	7/13	2887	2719	4874	142	39350	655	484
	2003	5/17	8/22	7/15	2417	2824	4744	97	34162	704	505
Toby	2000	5/16	9/23	8/3	2671	3251	5411	130	42901	616	658
	2001	6/7	9/30	7/14	3134	2858	5211	116	39085	929	408
	2002	4/26	9/30	7/18	3176	2701	5473	158	45616	668	514
	2003	4/30	9/9	7/20	2726	2673	4856	132	37323	601	606
Two creek	2000	5/18	9/20	7/28	2696	3062	5360	126	41427	709	598
	2001	5/19	9/24	7/23	2973	2699	4844	129	39424	537	447
	2002	5/4	10/1	7/14	2761	2626	5098	150	41867	760	458
	2003	5/10	9/9	7/10	2408	2732	5028	123	38156	847	497
Willow	2000	5/15	9/30	7/19	2742	2845	5548	138	43942	829	531
	2001	5/15	10/1	7/17	2885	2588	5367	141	42607	802	507
	2002	5/3	10/8	7/3	3106	2568	5359	159	45675	820	408
	2003	5/5	9/8	7/24	2476	2649	5278	126	40041	732	667

[1] mm/dd
[2] VI units * 10,000
[3] Number of days
[4] (VI units/composite period) * 10,000.

Table 5-2: Mean of EVIm based VPMs for 2000-2003 for 16 watersheds.

Watersheds	Year	Onset date[1]	End date[1]	Peak date[1]	Onset value[2]	End value[2]	Peak value[2]	Len-gth[3]	Time-int.VI[2]	Rt of green up[4]	Rt of sense-cence[4]
1A	2000	5/31	9/7	7/24	3129	3363	5584	100	35925	1186	771
	2001	5/14	9/17	8/6	3213	2887	4513	126	38930	363	436
	2002	5/4	9/15	7/4	3272	2851	5081	135	41332	805	399
	2003	5/28	8/26	7/6	2975	2928	5103	91	34228	1165	516
Burnt pine	2000	5/31	10/1	7/24	3503	3038	6013	124	45970	1102	602
	2001	5/15	9/26	7/27	3083	2793	5236	135	44037	732	498
	2002	5/7	10/3	7/18	3215	2914	5165	150	45043	745	405
	2003	5/8	9/7	7/2	2750	2768	5565	123	40403	1238	551
Cassidy	2000	5/18	9/13	7/19	3390	3626	6039	119	43514	984	563
	2001	5/28	9/3	7/13	3588	3197	5991	99	36825	1713	850
	2002	4/19	9/30	7/10	3788	2794	5436	165	49187	792	467
	2003	5/15	9/4	7/19	2913	2846	5411	113	39792	756	625
Chickadee	2000	5/22	9/16	7/21	3007	3037	5280	118	39154	941	540
	2001	5/26	9/11	7/10	3358	2874	5348	109	36870	1239	526
	2002	5/8	9/20	7/10	3074	2649	4954	135	39959	860	431
	2003	5/9	9/3	7/18	2804	2686	4899	118	36919	697	572
Fireweed	2000	6/16	9/19	8/12	2769	2598	4539	96	29007	725	610
	2001	5/16	9/10	7/27	2810	2571	4924	118	34527	848	585
	2002	5/8	9/18	7/22	2611	2332	4390	134	33403	791	444

	2003	5/15	9/8	7/26	2256	2583	4549	117	31424	683	560
Goose	2000	6/17	9/9	8/2	2610	2528	4398	86	29625	777	499
	2001	5/20	9/13	7/31	2413	2386	4424	116	31076	645	520
	2002	5/16	9/7	7/18	2499	2385	4364	116	31040	772	455
	2003	5/14	9/13	7/29	2303	2239	4343	123	30931	601	555
Kashka	2000	5/20	9/12	7/28	2629	2850	4328	115	32780	498	409
	2001	5/18	9/3	7/8	2909	2471	4699	109	31533	1044	520
	2002	5/5	8/10	7/3	2759	2668	4279	98	30954	707	399
	2003	4/30	8/28	7/10	2721	2432	4610	121	31766	904	491
Millions	2000	5/14	9/6	7/12	3248	3421	4820	116	34856	682	459
	2001	5/26	8/8	6/25	3639	3303	4880	75	28215	907	524
	2002	5/4	8/25	6/15	3623	3084	4541	114	34812	703	254
	2003	5/2	8/17	7/1	3423	2943	4347	109	32185	610	327
Mosquito	2000	5/23	9/27	7/11	2898	2800	5474	128	41108	1090	481
	2001	5/29	9/15	7/1	3055	2572	5452	110	35789	1619	563
	2002	4/18	9/28	6/22	2832	2490	4952	164	42052	1111	377
	2003	5/12	9/6	7/19	2694	2328	4981	118	35859	807	648
Pierre	2000	6/5	9/13	8/4	2760	2940	4523	102	32106	735	576
	2001	5/25	9/21	7/30	3402	2646	4553	120	32419	666	510
	2002	5/15	9/29	7/22	3231	2685	4443	138	35281	638	365
	2003	5/7	9/8	7/18	2747	2824	4790	125	35530	648	639
Sak A	2000	6/1	9/23	7/29	3085	2885	5215	114	38440	906	570
	2001	5/20	9/16	7/27	2999	2692	4829	120	36538	684	501
	2002	5/4	9/19	7/14	3015	2592	4887	140	39994	767	449
	2003	5/16	9/5	7/14	2682	2652	4905	113	35394	882	518
Sak B	2000	5/15	10/2	8/6	2592	2823	5642	142	45368	730	634
	2001	5/23	9/28	7/16	2892	2763	5810	129	42234	1253	578
	2002	5/16	9/27	7/20	2659	2575	4971	136	38560	914	455
	2003	5/4	9/26	7/27	2095	2270	5194	146	38270	805	685
Thistle	2000	5/25	9/4	7/19	3089	2986	4933	103	34660	821	579
	2001	5/25	8/28	7/15	3304	2823	4809	97	33446	790	535
	2002	5/3	9/13	7/13	3093	2733	4882	133	38776	856	496
	2003	5/23	8/18	7/16	2647	2816	4728	89	32765	759	534
Toby	2000	5/27	9/19	8/3	2919	3231	5315	116	38571	857	668
	2001	6/9	9/20	7/15	3450	2857	5217	104	35698	1261	451
	2002	4/30	9/24	7/17	3414	2785	5480	148	43760	839	538
	2003	5/5	9/5	7/22	3035	2755	4822	124	35901	570	615
Two creek	2000	5/23	9/15	7/30	2929	3057	5308	116	38351	890	652
	2001	5/25	9/17	7/24	3215	2723	4839	117	36982	678	469
	2002	5/9	9/23	7/16	3113	2652	5083	138	40163	864	488
	2003	5/13	9/4	7/11	2735	2727	5020	115	36957	901	517
Willow	2000	5/22	9/22	7/20	3101	2916	5550	123	41137	1050	550
	2001	5/21	9/22	7/19	3174	2682	5348	125	39469	1192	543
	2002	5/7	9/30	7/4	3380	2573	5347	147	44105	1061	426
	2003	5/10	9/3	7/25	2806	2601	5245	117	38712	743	700

[1] mm/dd
[2] VI units * 10,000
[3] Number of days
[4] (VI units/composite period) * 10,000.

Table 5-3: Mean of NDVIz based VPMs for 2000-2003 for 16 watersheds.

Watersheds	Year	Onset date[1]	End date[1]	Peak date[1]	Onset value[2]	End value[2]	Peak value[2]	Len-gth[3]	Time-int.VI[2]	Rt of green up[4]	Rt of sense-cence[4]
1A	2000	4/28	11/4	8/25	6322	4991	8681	191	100698	414	908
	2001	4/18	11/1	9/7	6432	6644	8701	197	98220	416	851
	2002	5/5	11/1	8/24	2819	6341	8704	180	96212	860	564
	2003	4/4	10/24	7/26	3668	5301	8716	204	102581	747	553
Burnt pine	2000	5/11	11/5	8/1	6649	6004	8887	179	100937	533	515
	2001	3/24	10/23	7/24	5574	7237	8668	214	102326	559	408
	2002	5/1	10/17	8/20	2038	6789	8618	170	90511	847	444
	2003	4/9	10/31	7/28	3080	4935	8591	207	97361	834	582
Cassidy	2000	5/15	11/9	8/22	6773	5018	9037	179	104552	455	785
	2001	5/9	10/29	8/14	6696	6937	8803	173	92937	478	498
	2002	4/18	11/3	8/15	3686	6583	8904	201	102274	783	546
	2003	4/13	11/15	7/30	4631	4442	8759	218	106910	632	579
Chickadee	2000	5/13	11/6	8/22	6048	4970	8595	178	93576	491	769
	2001	4/21	11/7	8/2	5682	5660	8724	201	99991	662	770
	2002	4/28	11/6	8/20	2143	5591	8391	193	91066	877	603
	2003	4/12	11/9	8/4	3126	3512	8404	212	97247	772	775
Fireweed	2000	5/28	10/8	8/15	4598	5107	7570	134	64184	662	654
	2001	4/8	10/13	8/2	4391	5245	7770	189	81863	536	719
	2002	4/19	10/6	8/14	514	5876	7465	170	67601	738	442
	2003	3/31	11/24	8/2	1144	1588	7633	238	78272	930	782
Goose	2000	5/6	10/17	8/14	4035	4819	7392	165	73006	631	623
	2001	4/9	10/27	8/8	3843	4437	7408	202	80096	557	648
	2002	4/24	10/18	8/14	1163	5366	7480	178	69885	906	558
	2003	4/13	11/12	8/7	1641	2000	7508	214	77272	924	838
Kashka	2000	6/11	11/12	9/5	6782	4175	8329	155	81691	380	923
	2001	4/28	11/5	8/5	5790	5641	8546	192	96038	643	1113
	2002	4/22	11/13	9/3	1518	5226	8144	206	89225	773	850
	2003	4/2	11/6	8/18	3271	2619	8098	220	96070	575	1037
Millions	2000	4/18	11/12	9/6	6701	4297	8509	209	112731	289	969
	2001	4/11	11/12	7/19	6629	6072	9170	216	116969	490	670
	2002	4/29	11/15	9/2	3542	5773	8456	200	105953	760	623
	2003	4/13	10/28	8/19	3831	4363	8396	199	105438	596	844
Mosquito	2000	4/24	11/16	8/20	5487	4466	8606	207	97030	505	736
	2001	4/13	11/5	7/21	5282	5769	8558	207	95363	655	462
	2002	4/17	11/14	8/12	2685	5276	8419	212	90382	844	577
	2003	4/5	11/19	8/15	2600	3463	8552	229	98281	736	805
Pierre	2000	5/10	11/9	9/4	5783	4432	7774	184	88574	365	777
	2001	4/18	11/5	8/24	5489	5891	8294	201	96539	454	875
	2002	5/6	10/14	8/19	2112	6689	8200	162	81765	803	421
	2003	4/15	11/3	8/22	4307	3247	8266	203	96890	491	961
Sak A	2000	5/5	11/2	8/18	5443	5137	8316	182	90833	533	673
	2001	4/20	11/1	8/14	5483	5513	8293	196	96972	498	753
	2002	4/29	10/31	8/21	1914	5865	8296	185	86539	887	586
	2003	4/10	11/13	8/4	2386	3642	8200	218	92519	867	690
Sak B	2000	4/19	11/5	8/7	4012	5034	8571	201	92828	714	584
	2001	4/9	10/26	8/9	4107	5475	8581	200	91709	691	951

	2002	4/3	11/8	8/8	674	4313	7985	220	82115	981	817
	2003	3/19	11/23	7/24	1848	2414	8151	250	83469	861	766
Thistle	2000	4/26	11/4	8/27	5935	4555	8402	193	97510	438	953
	2001	3/30	11/5	8/22	5366	5609	8281	221	102849	519	927
	2002	5/1	11/8	9/1	2337	5431	8304	193	90633	833	732
	2003	3/29	11/7	8/1	2946	3829	8303	224	98682	752	708
Toby	2000	4/27	11/5	8/2	6002	5269	8538	193	94571	607	535
	2001	4/26	11/2	8/20	5876	5539	8740	191	102322	521	933
	2002	5/6	10/5	8/10	2393	6821	8418	152	83923	925	381
	2003	4/4	11/6	8/5	3448	2987	8394	217	101200	665	839
Two creek	2000	5/16	11/4	8/24	6002	4971	8650	172	92460	504	808
	2001	4/7	11/4	8/15	5490	5288	8516	212	104114	496	836
	2002	4/29	11/11	8/14	2111	5143	8530	196	91071	952	587
	2003	4/8	11/11	8/1	3060	3603	8526	218	98783	811	748
Willow	2000	5/9	11/3	8/15	5945	5019	8632	179	90722	563	695
	2001	4/9	10/30	8/17	5225	5774	8542	205	99141	529	732
	2002	4/20	11/5	8/13	2046	5591	8517	200	87848	946	629
	2003	4/1	11/17	7/27	2904	3626	8563	230	98434	799	659

[1] mm/dd
[2] VI units * 10,000
[3] Number of days
[4] (VI units/composite period) * 10,000.

Table 5-4: Mean of NDVIm based VPMs for 2000-2003 for 16 watersheds.

Watersheds	Year	Onset date[1]	End date[1]	Peak date[1]	Onset value[2]	End value[2]	Peak value[2]	Length[3]	Time-int.VI[2]	Rt of green up[4]	Rt of sense-cence[4]
1A	2000	5/3	11/5	8/26	6575	4460	8676	188	99883	400	1021
	2001	4/21	11/4	9/8	6462	6048	8703	198	103752	369	1093
	2002	5/11	10/27	8/24	3148	6203	8682	170	95421	873	612
	2003	4/16	10/22	7/26	4277	5001	8747	189	99035	784	587
Burnt pine	2000	5/4	11/10	8/1	6455	4426	8663	191	100009	572	713
	2001	3/25	11/2	7/31	5607	6332	8702	223	107817	510	685
	2002	5/9	10/23	8/22	2784	6359	8632	168	92908	870	510
	2003	4/21	10/25	7/30	3862	4641	8597	188	93971	825	674
Cassidy	2000	5/8	11/10	8/19	6824	4313	9051	187	104429	418	842
	2001	5/11	11/5	8/14	6775	5781	8821	179	98388	507	743
	2002	4/28	11/3	8/17	4270	6134	8915	190	100997	811	628
	2003	4/24	11/3	7/30	5258	4481	8759	194	100210	642	623
Chickadee	2000	5/14	11/6	8/22	6327	4326	8601	177	93866	486	842
	2001	4/24	11/7	8/3	5834	4968	8749	198	101097	784	941
	2002	5/7	11/3	8/22	2593	5318	8401	181	91221	926	697
	2003	4/22	11/1	8/4	3625	3408	8406	194	94111	804	833
Fireweed	2000	6/2	10/9	8/15	4797	4787	7597	130	61425	735	684
	2001	4/7	10/12	8/2	4359	4726	7788	189	83690	532	763
	2002	5/1	10/21	8/17	577	5039	7459	174	70312	965	606
	2003	4/18	11/11	8/2	2722	1501	7633	208	76289	916	859

Goose	2000	5/11	10/16	8/14	4242	4493	7403	159	71874	677	665
	2001	4/9	10/22	8/8	3672	4184	7405	196	79851	587	715
	2002	5/6	10/22	8/16	1496	4849	7471	170	71055	1036	667
	2003	4/27	11/3	8/8	2827	1909	7511	191	75862	886	895
Kashka	2000	6/3	11/10	8/31	6630	3893	8335	160	82103	415	901
	2001	4/27	11/4	8/14	5844	5138	8641	192	96812	760	1495
	2002	5/2	11/10	9/4	1857	4998	8162	193	90887	824	915
	2003	4/14	10/31	8/18	3628	2548	8098	201	92555	603	1077
Millions	2000	4/19	11/9	9/5	7517	4129	8525	205	113467	186	956
	2001	4/13	11/10	7/19	6773	5807	9179	213	117349	517	695
	2002	5/3	11/11	9/3	3922	5682	8457	193	105887	668	643
	2003	4/21	10/25	8/19	4219	4363	8396	188	102573	596	847
Mosquito	2000	4/27	11/10	8/19	5588	3940	8610	198	97383	533	807
	2001	4/18	11/4	7/27	5234	4816	8590	202	96115	638	612
	2002	4/27	11/11	8/14	3435	4687	8430	199	92450	823	656
	2003	4/17	11/7	8/15	2960	3345	8552	206	95296	783	886
Pierre	2000	5/10	11/7	9/3	5910	4230	7831	182	89626	377	833
	2001	4/18	11/4	8/28	5473	5693	8277	201	97883	502	1059
	2002	5/14	10/11	8/19	2736	6584	8196	150	79068	877	461
	2003	4/27	10/29	8/23	4871	3112	8266	187	92725	479	1000
Sak A	2000	5/6	11/2	8/18	5575	4366	8320	181	91003	558	766
	2001	4/22	11/2	8/15	5533	4892	8299	195	97239	533	892
	2002	5/	10/29	8/23	2272	5529	8284	176	87234	955	677
	2003	4/22	11/5	8/5	3278	3391	8210	197	90087	858	768
Sak B	2000	5/1	11/5	8/8	4508	4108	8565	189	91171	758	701
	2001	4/14	10/24	8/9	4100	5040	8526	194	89394	754	1056
	2002	4/21	11/5	8/9	1158	3768	7974	199	81974	1092	901
	2003	4/7	11/10	7/24	2101	1620	8151	219	81599	998	895
Thistle	2000	4/28	11/3	8/27	6274	4042	8403	190	98494	426	1023
	2001	4/1	11/6	8/27	5363	4984	8307	220	106160	539	1161
	2002	5/8	11/6	9/2	2675	5096	8329	183	91292	872	816
	2003	4/11	10/30	8/1	3379	3766	8303	203	95298	829	741
Toby	2000	4/27	11/9	8/1	6118	4417	8566	197	99081	711	643
	2001	4/30	11/3	8/22	5934	5211	8738	189	101083	648	1059
	2002	5/14	10/3	8/10	2948	6697	8446	143	82924	946	398
	2003	4/17	10/31	8/5	4224	2987	8394	198	97207	649	850
Two creek	2000	5/18	11/4	8/24	6192	4150	8652	171	91665	509	926
	2001	4/10	11/6	8/17	5535	4379	8532	210	104860	515	1053
	2002	5/8	11/5	8/14	2435	4865	8533	182	90721	1026	646
	2003	4/20	11/2	8/1	3779	3462	8525	197	94966	825	800
Willow	2000	5/5	11/4	8/11	5929	3984	8680	184	92394	572	796
	2001	4/11	11/4	8/19	5257	4741	8553	208	100217	533	941
	2002	5/1	11/5	8/14	2515	5033	8545	188	89673	1062	718
	2003	4/16	11/5	7/27	3476	3522	8555	204	93655	857	724

[1] mm/dd
[2] VI units * 10,000
[3] Number of days
[4] (VI units/composite period) * 10,000.

Table 5-5: Mean, standard deviation and ANOVA p-values for the four comparative approaches.

VPMs	Year	Four comparative approaches								ANOVA p-value
		M1 (EVIm)		M2 (NDVIm)		M3 (EVIz)		M4 (NDVIz)		
		Mean	St_dev	Mean	St_dev	Mean	St_dev	Mean	St_dev	
Onset date	2000	148.6	10.0	129.6	12.3	142.0	10.9	128.8	14.2	< 0.001
	2001	144.7	6.4	107.7	11.5	138.6	8.3	105.8	11.5	< 0.001
	2002	126.7	7.9	126.4	6.3	122.1	7.1	117.0	8.6	< 0.001
	2003	132.8	7.4	110.3	5.5	127.2	8.1	97.5	7.2	< 0.001
End date	2000	261.1	8.5	309.0	9.1	266.5	10.4	309.2	9.6	< 0.001
	2001	256.8	12.6	307.1	7.4	265.2	12.0	306.0	7.0	< 0.001
	2002	262.6	14.5	304.1	11.3	268.7	14.9	304.7	13.9	< 0.001
	2003	248.1	9.3	306.8	5.6	252.7	9.8	315.3	8.7	< 0.001
Peak date	2000	208.7	9.0	232.6	10.6	207.8	9.3	233.5	11.0	< 0.001
	2001	200.8	11.6	226.1	13.2	200.5	11.4	223.4	13.3	< 0.001
	2002	193.1	10.6	233.7	8.2	191.6	12.2	232.4	8.2	< 0.001
	2003	199.0	8.6	218.5	9.0	197.8	8.7	218.2	9.0	< 0.001
Onset value	2000	2978.6	269.6	5966.3	866.3	2722.1	249.1	5782.3	889.8	< 0.001
	2001	3156.5	314.0	5484.7	870.0	2882.8	321.8	5459.7	811.1	< 0.001
	2002	3098.6	362.8	2551.3	957.8	2828.9	367.5	2105.9	871.9	< 0.001
	2003	2724.1	316.1	3655.4	810.0	2411.4	366.2	2993.2	930.0	< 0.001
End value	2000	3006.2	290.1	4254.0	238.9	3003.8	298.5	4891.5	442.7	< 0.001
	2001	2765.0	237.8	5171.3	602.8	2727.4	227.8	5795.7	679.2	< 0.001
	2002	2672.6	191.4	5427.6	798.3	2686.1	208.7	5792.1	701.7	< 0.001
	2003	2649.9	225.5	3316.1	1039.9	2665.6	216.0	3473.2	1008.9	< 0.001
Peak value	2000	5185.1	544.5	8417.4	445.7	5207.8	553.4	8405.6	453.7	< 0.001
	2001	5054.5	455.4	8488.1	418.6	5063.4	453.2	8474.7	414.7	< 0.001
	2002	4890.9	386.5	8307.3	396.0	4909.8	384.8	8301.9	391.0	< 0.001
	2003	4907.0	350.4	8318.9	350.3	4911.6	345.8	8316.3	348.6	< 0.001
Length	2000	113.6	13.6	180.6	18.4	125.4	16.4	181.3	19.1	< 0.001
	2001	113.1	14.6	200.4	11.8	127.6	14.7	201.1	11.9	< 0.001
	2002	136.9	17.2	178.7	16.1	147.6	17.3	188.6	18.8	< 0.001
	2003	116.4	13.2	197.8	8.8	126.4	15.2	218.8	13.4	< 0.001
Time-int. VI	2000	37535	5193	92367	12408	40326	5889	92243	11727	< 0.001
	2001	35911	4107	98856	9105	38784	4189	97340	8628	< 0.001
	2002	39276	5143	88376	9549	40857	5359	87937	9896	< 0.001
	2003	35439	3015	92214	7817	36804	2896	95588	8718	< 0.001
Rt of greenup	2000	873.4	182.2	520.8	152.5	691.8	134.7	505.3	114.6	< 0.001
	2001	977.1	374.7	576.8	112.4	715.1	211.2	544.0	79.9	< 0.001
	2002	826.6	123.4	914.1	109.8	701.2	84.3	857.2	73.3	< 0.001
	2003	798.1	189.0	770.9	138.3	737.1	162.0	749.5	127.8	< 0.001
Rt of senescence	2000	572.7	87.9	819.9	121.7	542.0	86.2	744.2	144.4	< 0.001
	2001	538.1	92.8	935.2	229.5	490.6	63.0	759.1	191.6	< 0.001
	2002	428.0	64.8	659.4	139.0	407.9	58.6	585.0	131.9	< 0.001
	2003	565.8	90.0	816.2	129.1	541.6	87.0	760.4	132.8	< 0.001

Table 5- 6: Homogenous subsets of VPMs based on Tukey HSD multiple comparison test.

VPMs	Year	Subset 1	p-value	Subset 2	p-value	Subset 3	p-value
Onset date	2000	M1, M3	0.412	M2, M4	0.998		
	2001	M1, M3	0.942	M2, M4	0.291		
	2002	M1, M3	0.238	M1, M2, M4	0.317		
	2003	M1, M3	0.13	M2	1	M4	1
End date	2000	M1, M3	0.382	M2, M4	1		
	2001	M1, M3	0.096	M2, M4	0.988		
	2002	M1, M3	0.592	M2, M4	0.999		
	2003	M1, M3	0.433	M2	1	M4	1
Peak date	2000	M1, M3	0.994	M2, M4	0.995		
	2001	M1, M3	1	M2, M4	0.93		
	2002	M1, M3	0.977	M2, M4	0.981		
	2003	M1, M3	0.981	M2, M4	1		
Onset value	2000	M1, M3	0.678	M2, M4	0.852		
	2001	M1, M3	0.618	M2, M4	1		
	2002	M1, M3	0.129	M2, M4	0.28		
	2003	M1, M3, M4	0.073	M2	1		
End value	2000	M1, M3	1	M2	1	M4	1
	2001	M1, M3	0.996	M2	1	M4	1
	2002	M1, M3	1	M2, M4	0.25		
	2003	M1, M2, M3	0.063	M4	1		
Peak value	2000	M1, M3	0.999	M2, M4	1		
	2001	M1, M3	1	M2, M4	1		
	2002	M1, M3	0.999	M2, M4	1		
	2003	M1, M3	1	M2, M4	1		
Length	2000	M1, M3	0.214	M2, M4	0.999		
	2001	M1	1	M2, M4	0.999	M3	1
	2002	M1, M3	0.312	M2, M4	0.376		
	2003	M1, M3	0.134	M2	1	M4	1
Time-integrated VI	2000	M1, M3	0.835	M2, M4	1		
	2001	M1, M3	0.646	M2, M4	0.926		
	2002	M1, M3	0.94	M2, M4	0.999		
	2003	M1, M3	0.925	M2, M4	0.424		
Rate of greenup	2000	M1	1	M2, M4	0.991	M3	1
	2001	M1	1	M2, M3, M4	0.152		
	2002	M1, M2, M4	0.073	M3	1		
	2003	M1, M2, M3, M4	0.688				
Rate of senescence	2000	M1, M3	0.868	M2, M4	0.239		
	2001	M1, M3	0.834	M2	1	M4	1
	2002	M1, M3	0.949	M2, M4	0.2		
	2003	M1, M3	0.927	M2, M4	0.497		

N = 16, M1 = EVIm, M2 = NDVIm, M3 = EVIz, M4 = NDVIz

5.1 Comparison of Four Approaches Used to Derive VPMs

Methodologies employed by researchers for detecting phenological transition dates from the satellite VI data (see Literature Review II) are somewhat arbitrary (White et al. 1997) and may yield significantly different results. Therefore, the phenological information provided by the four approaches needs to be investigated and compared. Results then must be interpreted and discussed in the specific context of the method used.

5.1.1 Zhang versus Zhang modified approach

In general, the OG date derived from the Zhang modified approach tends to occur slightly later than Zhang approach, while the EG date occurs slightly earlier. This results in a shorter length of growing season for the Zhang modified approach. However, there are a few exceptions to this general trend in NDVI VPMs. The length of the growing season is, in fact, longer in the modified approach for the year 2001 for the 1A, Burnt pine, Cassidy, Fireweed, Pierre and Thistle watersheds. Visual observation of the Table 5-1, 5-2, 5-3 and 5-4 reveals that overall the difference between VIm (EVIm and NDVIm) and VIz (EVIz and NDVIz) VPMs is not substantial. The maximum difference for EVI based OG and EG dates is 15 and 12 days, respectively, and for NDVI based OG and EG dates it is 19 and 15 days, respectively. The maximum EVI based OG date and EG date difference in the two approaches is for the Fireweed watershed in 2003 and Cassidy watershed in 2001, respectively and the NDVI based maximum OG date and EG date difference is for Sak B in year 2003 and for Fireweed in year 2002, respectively. These watershed level differences in OG and EG dates for the two approaches can be attributed to random error and data temporal resolution limitations.

Both of the approaches yield almost the same peak date and peak VI value for both the EVI and NDVI. Almost 3 to 10 times greater differences can be seen between the two approaches for the NDVI based OG VI value, EG VI value and time integrated VI value when compared to EVI based values because of the higher NDVI amplitude as compared to the EVI. A higher rate of greenup and senescence for Zhang modified approach was observed compared to Zhang approach with few exceptions in the NDVI based rate metrics. The most notable difference of 661 for greenup and 186 for senescence rates in the two EVI based approaches were seen for the Cassidy watershed in 2001.

The above visual observations are supported by Tukey HSD MCT results in Table 5-6. EVIm and EVIz (M1 and M3) derived VPMs are grouped together in the homogenous subset 1 for almost all of the VPMs in the four years. The exceptions to this trend are for the length of growing season metric in 2001 and the rate of greenup metric in 2000, 2001 and 2002. Likewise, NDVIm and NDVIz (M2 and M4) VPMs are coupled together in homogenous subset 2 most of the time. The instances when NDVIm and NDVIz derived VPMs are different are the OG date in 2003, EG date in 2003, OG value in 2003, EG value in 2000, 2001 and 2003, rate of greenup in 2002 and rate of senescence in 2001. A pattern can be identified by these exceptions: the Zhang method and Zhang modified method yield significantly different VPMs for 2003 MODIS NDVI data. This implies that 2003 MODIS NDVI data is sensitive to both the Zhang and Zhang modified approach in contrast to MODIS 2000, 2001 and 2002 NDVI and the four year MODIS EVI data. This is also supported by the fact that the time integrated VI metric has the lowest p-value for the M2, M4 pair in 2003. Increasing p-values in Table 5-6 above the alpha level of 0.05 reflect the degree of insignificance between class (M1, M2, M3 and M4) differences (p-value > 0.05 implies insignificant differences). EVI and NDVI based peak date and VI value and time integrated VI value are the most perfectly grouped metrics for both of the approaches. It is important to note that for the peak date metric, a difference of less than 16 days implies no significant difference because 16 is the minimum temporal resolution of the data.

5.1.2 EVI versus NDVI algorithm

VPMs derived from EVI and NDVI are quite different among the four years. NDVI identifies a very early OG date in April and a delayed EG date in November when compared to the EVI based OG date in May and EG date in September. All VPMs for the four years differ for NDVI and EVI except for the OG date metric in 2002 when M1, M3, and M4 are grouped together; the OG value metric in 2003 when M1, M3, and M4 are grouped together; and EG value metric in 2003 when M1, M2, and M3 are grouped together in the same homogenous subset (see Table 5-6). The rate of greenup metric exhibits the most serious deviation from the observed trend since M2, M3, M4 for year 2001; M1, M3, M4 for the year 2002; and M1, M2, M3, M4 for the year 2003 are

coupled together in the same homogenous subset. These exceptions can be partly attributed to already observed unique behavior of 2003 NDVI data, which yields significantly different VPMs for the Zhang and Zhang modified approaches. The result is the random coupling of M2 (NDVIm) and M4 (NDVIz) with M1 (EVIm) and M3 (EVIz) in the same homogenous subset.

To investigate further into the different responses of MODIS NDVI versus EVI, to extract VPMs, the Pearson correlation coefficient between raw and treated EVI and NDVI for each pixel (including all 23 composite periods) was first computed and then spatially averaged over each watershed for each year. A weak correlation between NDVI and EVI can be seen in Table 5-7.

Table 5-7: Mean of Pearson correlation coefficients between per-pixel NDVI and EVI for 2000 to 2003.

Watersheds	Raw data				Treated data			
	2000	2001	2002	2003	2000	2001	2002	2003
1A	0.51	0.37	0.54	0.51	0.47	0.43	0.46	0.48
Burnt pine	0.53	0.46	0.56	0.55	0.66	0.67	0.57	0.63
Cassidy	0.49	0.37	0.49	0.68	0.55	0.47	0.50	0.55
Chickadee	0.51	0.39	0.54	0.49	0.53	0.49	0.49	0.45
Fireweed	0.59	0.54	0.63	0.64	0.62	0.62	0.55	0.50
Goose	0.67	0.66	0.67	0.69	0.63	0.62	0.58	0.56
Kashka	0.43	0.34	0.42	0.48	0.36	0.45	0.27	0.28
Millions	0.30	0.14	0.33	0.23	0.38	0.27	0.27	0.07
Mosquito	0.62	0.54	0.56	0.60	0.66	0.66	0.58	0.57
Pierre	0.41	0.35	0.52	0.34	0.49	0.45	0.34	0.38
Sak A	0.55	0.45	0.54	0.61	0.61	0.54	0.50	0.55
Sak B	0.78	0.71	0.71	0.80	0.74	0.79	0.61	0.66
Thistle	0.34	0.32	0.50	0.46	0.28	0.31	0.48	0.30
Toby	0.41	0.37	0.44	0.30	0.51	0.47	0.28	0.37
Two creek	0.56	0.45	0.60	0.57	0.56	0.45	0.56	0.52
Willow	0.56	0.47	0.58	0.59	0.58	0.59	0.55	0.54
All area	0.57	0.48	0.58	0.59	0.58	0.53	0.52	0.52

The effect of data treatment on the correlation coefficient was mixed. In some cases it improved the coefficient by as much as 0.22 while in other cases it reduced the

coefficient by as much as 0.18. Moreover, visual analysis of a large number of pixels revealed that the big modes in the vegetation growth cycles frequently did not line up between NDVI and EVI. In theory, the indices should be very highly correlated: timings of major changes of the two VI methods should differ very slightly with scale differences serving as the primary distinction. Comparisons made at the Kansas Applied Remote Sensing Laboratory revealed that the correlation coefficients were almost always greater than 0.9 (Kastens 2004, verbal communication).

MODIS' "Known Product Issues" website (LDOPE 2004) has also acknowledged the inconsistent NDVI versus EVI values under certain conditions in collection 4 VI data (Case #: DR_MOD13_01274; Opening date: October 1 2001; Last updated: September 6 2004; Status: Pending). NDVI and EVI values were significantly uncorrelated for the Okavango Delta in Botswana, with the scatter plot indicating a strong land cover dependency of the effect.

The early prediction of NDVI based OG date and NDVI's weak correlation to the EVI data can be attributed to the way the NDVI algorithm is designed (see Literature Review I under MODIS NDVI). The enhanced sensitivity of the NDVI algorithm over low biomass regions is achieved at the expense of reduced sensitivity at the high biomass regions, resulting in the NDVI saturation problems. The EVI, being a non-ratio index, responds more linearly to the variations in high biomass regions. It was found to perform well in the heavy aerosol, biomass burning conditions in Brazil (Miura et al. 1998).

Theoretically, the EVI algorithm is expected to perform better than the NDVI to monitor vegetation dynamics for the FORWARD study area because of the open canopy. Such canopies have significant background contamination that adversely impacts the canopy's reflectance properties (Graetz 1990). The EVI isolates the green photosynthetically active reflectance signal from the spatially and temporally variable background effect, only taking the upper-storey (forest canopy) reflected radiations into account, to allow for more meaningful inter-comparisons. On the other hand, NDVI variations are induced by canopy background contamination that includes soils, leaf litter, water, and weathered geologic substrates such as peat, moss, etc. However, one major

factor contributing to the weak correlation of NDVI versus EVI for the FORWARD study area is the presence of snow during the winter months. While NDVI algorithm exhibits extremely low values, the EVI algorithm results in abnormally high values for the snow because it employs the blue reflectance term that for snow is higher than the green, red and NIR reflectances (see Figure 2-1 Literature Review-I section). NDVI values for snow are either zero or negative since snow has higher red than the NIR reflectance. This reasoning is further supported below (see section 5.4 Environmental Control of Vegetation Phenology) and was also confirmed by the improved correlation coefficient (0.7 to 0.9) when the winter NDVI and EVI (or snow NDVI and EVI) values were removed from the correlation coefficient computation.

The FORWARD study area, covered with snow in the months of March and April, is an important consideration regarding the OG date detection. Average snow depth recorded by Environment Canada's weather station at the Whitecourt airport location in Alberta (54° 8'-N 115° 47'-W, Elevation: 782.4 m) from 1971 to 2000, was 22, 25, 18 and 3 cm (median values were 22, 25, 18 and 1 cm) in January, February, March and April (Environment Canada 2004*c*). The highest snow depth of 700 mm was recorded in 1982 for the month of April (Environment Canada 2004*c*). Moreover, snow depth recorded for the period 1971 to 2000, at the end of April is zero (Environment Canada 2004*c*), which indicates that snowmelt always occurred before the end of April. Daily snow depth values for the period of 2000 to 2003 were also checked at Environment Canada's website for the Whitecourt weather station and it was confirmed that a trace amount of snow was found on the ground in the month of April and even in May. The VPM extraction algorithm employed in this study identifies the point of inflection, when the NDVI time-series curve exhibits the greatest increase in amplitude as the OG date. It appears that the OG point for the NDVI time-series data does not correspond to the canopy OG but represents the snow melt event, when the bare ground vegetation (shrubs, herbs, grass, and a thick organic layer) starts to show up and drastically increase NDVI values. The sudden jump in the NDVI amplitude is tagged as OG by the VPM extraction algorithm. This reasoning is consistent with statements by Schwartz and Reed (1999), who concluded that the consistent early OG dates were actually under-storey greenup

rather than canopy greenup dates, while using the AVHRR NDVI data to derive the OG and EG dates. Figure 5-2 and 5-3 depict a comparison of EVI versus NDVI data behavior for the Sak A watershed for all four years (2000 to 2003) and for the year 2001, respectively.

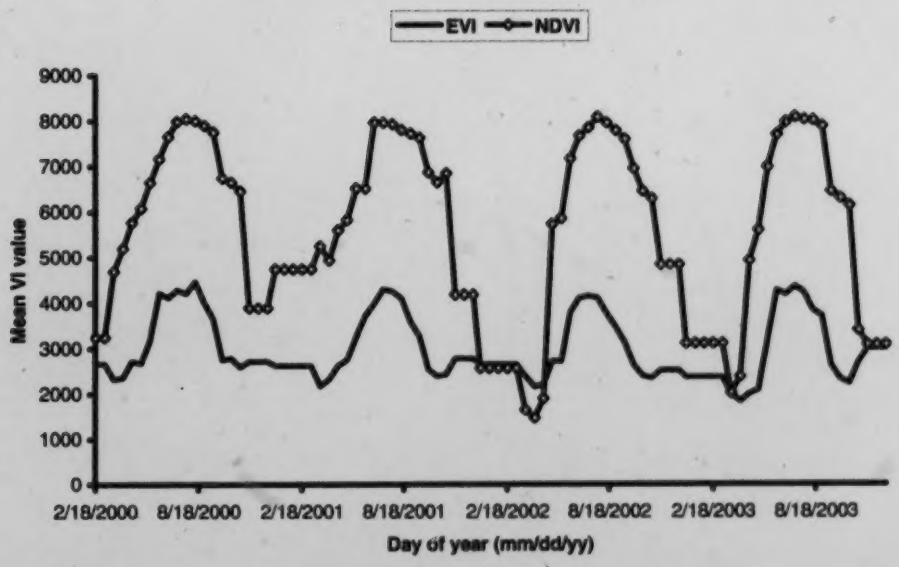

Figure 5-2: Comparison of time-series treated EVI versus NDVI for the Sak A watershed.

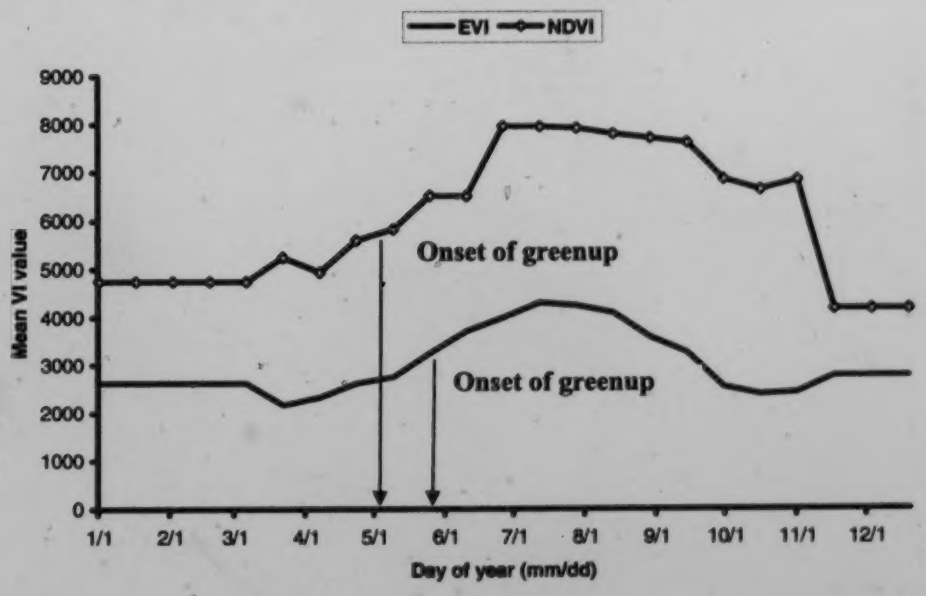

Figure 5-3: Comparison of 2001 treated EVI versus NDVI data for Sak A watershed.

5.2 Assess the Validity of VPMs

Validity of the VPMs was checked by examining the coincidence between satellite derived OG dates and actual ground based first bloom, full bloom, and leaf out event dates. Beaubien (2001) has compiled and reported first and full bloom dates for various indicator species in Alberta and the Northwest Territories (NWT) through the Plantwatch program (see Literature Review II section under Phenology) for the year 2001 (see Table 5-9). These phenological observations are based on the criteria set by the Plantwatch program protocols and are reproduced from the Plantwatch website (Beaubien 2003) as Table 5-8.

Table 5-8: Criteria for observing the first and full bloom dates of different plant species.

Species	First bloom	Full bloom
Aspen poplar	Half the catkins on the tree had started to shed pollen	Most of the catkins have turned pale yellow
Prairie crocus	At least two to five flowers have opened in a crocus patch, revealing the yellow stamens	Most blooms are open – not many new buds are left
Serviceberry	At least 50% of the flower clusters have at least one open flower	About 90% of the flower clusters no longer have any unopened flowers
Common purple lilac	At least 50% of the flower clusters had at least one open flower	About 95% of the flower clusters no longer had any unopened flowers but before many of the flowers have withered or dried up
Tamarack	The first pollen from male cones is being shed, in at least three different places	Half of the male cones are abundantly shedding pollen
Tamarack (leaf out event)	When, in at least three places on tree, the tuft of needles, after considerable lengthening, starts loosening up and spreading at the tip	

Aspen poplar (*Populus tremuloides*) is the major hardwood tree species in the western Canadian Boreal Forest and parkland and is by far the most abundant species (Peterson and Peterson 1992; Hogg 1994). It is the earliest flowering species in the growing season when compared to other native species such as serviceberry (*Amelanchier alnifolia*) and choke cherry (*Prunus virginiana*), and has a sharp first flowering (Beaubien and Freeland 2000). It produces flowers on an average of one month before the last killing frost (Lechowicz 1995) when spring temperatures above 12 °C last

for a duration of 6 days (Perala 1990). Bud development depends on the air temperature at the height of the buds (Lechowicz 1984). The earlier flowering species show more inter-annual variability in the bloom time as compared to later flowering species (Fitter et al. 1995). Hence, phenology of aspen poplar can be a sensitive indicator of climatic changes. Beaubien and Freeland (2000) studied the first-bloom dates for Aspen poplar in Edmonton, Alberta from a 20 year historical dataset and reported the mean first flowering date as April 13.

Table 5-9: Bloom dates for different indicator species in Alberta and NWT for the year 2001.

Species	Type	City, Province	First bloom	Full bloom	LAT-North	LONG-West
Aspen Poplar	Deciduous	Hay River, NWT	May 10	May 12	60.8234	115.7796
Aspen Poplar	Deciduous	Hay River, NWT	May 25*	May 28**	60.8234	115.7796
Aspen Poplar	Deciduous	Hay River, NWT		May 29**	60.8234	115.7796
Aspen Poplar	Deciduous	Near Lac La Biche, AB	May 12		54.7333	113.1031
Aspen Poplar	Deciduous	Devonian Botanic Garden, AB		April 17	53.46	113.83
Aspen Poplar	Deciduous	Devonian Botanic Garden, AB	May 2*	May 4**	53.46	113.83
Aspen Poplar	Deciduous	St. Paul, AB	April 17	April 27	53.9017	111.1681
Aspen Poplar	Deciduous	St. Paul, AB	April 30*	May 4**	53.9017	111.1681
Aspen Poplar	Deciduous	Cochrane, AB	May 18*	May 22**	51.28	114.68
Aspen Poplar	Deciduous	Sylvan Lake, AB	May 12*	May 14**	52	114
Service berry	Deciduous shrub	Devonian Botanic Garden, AB	May 18	May 21	53.46	113.83
Service berry	Deciduous shrub	Devonian Botanic Garden, AB	May 20	May 22	53.46	113.83
Service berry	Deciduous shrub	Devonian Botanic Garden, AB		May 24	53.46	113.83
Service berry	Deciduous shrub	St. Paul, AB		May 27	53.9017	111.1681
Purple lilac	Deciduous	Legal, AB	May 21	May 25	53.95	113.88
Purple lilac	Deciduous	Beaumont, AB	May 24	May 31	53.5	113.4167
Purple lilac	Deciduous	St. Paul, AB	May 26	June 3	53.9017	111.1681
Purple lilac	Deciduous	Devonian Botanic Garden, AB	May 25		53.46	113.83
Purple lilac	Deciduous	Fort McMurray, AB	May 28	June 3	56	111
Purple lilac	Deciduous	Hay River, NWT	June 12	June 19	60.8234	115.7796
Prairie crocus	Conifer shrub	Near Lac La Biche, AB		April 28	54.9608	112.4433
Prairie crocus	Conifer shrub	Sandy Lake, AB		May 20	60.5167	114.5833
Tamarack	Deciduous	Yellowknife, NWT	May 31		62.45	114.35
Tamarack	Deciduous	Yellowknife, NWT	June 2 (Leaf out)		62.45	114.35

* Leaves dime size
** Leaves quarter size

Dates marked with asterisk (*) and double asterisk (**), instead of first or full bloom, indicate the time when the leaves are of dime size and quarter size, respectively. First and full bloom date points towards the flowering, which, for these indicator species, often occurs before the leaves are fully developed. Satellite detected OG and EG are related to the level of photosynthetic activity in the ecosystem that neither strictly conceptualizes the exact ground based phenology events nor is consistent with budburst, first or full bloom, leaves dime size or leaves quarter size (for the OG event) and actual dormancy condition (for the EG event). However, satellite derived OG have been reported to occur after the initial leaf expansion and EG to coincide with a 15 to 50% leaf fall event (White et al. 1997).

Table 5-10 presents 16 FORWARD watershed's land cover composition as a percentage of each watershed area.

Table 5-10: FORWARD watersheds' land cover composition.

		Land cover unit (% watershed area)						
	Watersheds	Area (km^2)	Deciduous	Coniferous	Mixed woods	Range land	Peat lands	Urban industry & roads
Large burnt	Goose	150.57	13.97	65.72	7.83	4.13	7.86	0.48
	Sak A	233.93	2.81	72.61	5.18	9.68	9.21	0.47
Large unburnt	Chickadee	155.19	27.15	32.38	14.90	3.65	20.89	1.01
	Two creek	129.39	7.27	59.35	7.90	6.21	17.22	1.59
Small burnt	Burnt pine	7.66	0.32	66.86	1.44	21.27	10.1	0.00
	Fireweed	5.69	0.00	53.77	2.54	30.65	13.04	0.00
Small unburnt	1A	5.10	0.93	81.02	0.00	14.36	3.69	0.00
	Cassidy	5.87	31.74	28.14	39.41	0.00	0.15	0.03
	Kashka	3.91	41.27	22.12	27.28	0.00	5.07	4.26
	Millions	2.43	39.29	26.64	25.40	1.32	4.25	3.10
	Mosquito	3.07	59.16	13.92	21.62	0.00	2.64	2.67
	Pierre	2.58	35.77	48.32	7.33	4.19	0.53	3.85
	Sak B	7.04	38.25	15.08	21.34	1.21	24.12	0.00
	Thistle	9.01	59.03	13.81	13.44	3.71	5.29	4.71
	Toby	2.63	13.13	25.82	38.44	0.00	18.86	3.74
	Willow	15.57	42.61	27.91	23.20	1.87	3.4	1.02
	All area	739.65	13.70	56.83	9.42	6.42	12.63	0.89

* Percentages are computed from AVI using digital mapping techniques.

These statistics are computed by clipping the 1998 AVI (maintained by forestry companies) using each watershed polygon shape file in ArcGIS 8.2. Deciduous species inventoried in the AVI are Aspen poplar, Tamarack, Paper birch and Balsam poplar and conifers inventoried are Jack pine, Lodge pole pine, Sub-alpine fir, Balsam fir, Black spruce, and White spruce.

Mosquito, Thistle and Willow watersheds are dominated by deciduous tree species (see Table 5-10). The satellite detected OG dates (mm/dd) for these watersheds in the year 2001 is given in Table 5-11. EVI based OG dates occur in late May for the deciduous dominated watersheds while NDVI predicts it to be in early to mid-April. NDVI also shows greater variability in the OG date detection for these watersheds.

Table 5-11: Onset of Greenup (OG) date for the deciduous dominated watersheds in the year 2001.

Watersheds	EVIm	EVIz	NDVIm	NDVIz
Thistle	5/25	5/22	4/1	3/30
Mosquito	5/29	5/24	4/18	4/13
Willow	5/21	5/15	4/11	4/9

The FORWARD study area is close enough to the areas where ground observations are available for the year 2001. A comparison between Table 5-11 and Table 5-9 for deciduous species first, full and leafing dates and satellite OG dates suggests that satellite retrieved OG dates are realistic. Furthermore, based on the reasoning that leaf out date occurs one or two weeks after the full bloom date and that most of the deciduous indicator species (in Table 5-9) have their bloom or leafing date in mid- to late May (mean and median value of full bloom and leaves quarter size event dates are May 19 and May 22, respectively); EVIm (or EVIz since both methods yield similar VPMs) compares best among the four approaches to the observed onset-like events (first, full bloom and leaf size) on the ground for the year 2001. These results add confidence to the satellite retrieved OG dates.

A similar comparison could have been made for the conifer dominated watersheds, Two creek and 1A. However, none of the inventoried (for the AVI) conifer species' bloom dates could be found for the study area and thus are not reported. Although bloom dates of the conifer shrub, Prairie crocus in the year 2001 is reported in the Table 5-9, it is not inventoried in the AVI (though, there is a category of open and closed shrub in the AVI). A meaningful comparison of satellite derived OG dates for the Two creek and 1A watersheds and the conifer shrub 'Prairie crocus' full bloom dates could not be realized.

5.3 Characterizing the Spatial and Temporal Dynamics of Vegetation in each Watershed

Any time-series data can be explained in terms of two basic components: seasonality and trend. While the derived VPMs capture the seasonality of the VI time-series data, trend analysis is aided by correlating the mean VPM values and the standard deviation of the VPM. A strong correlation between the two indicates that seasonality fluctuates correspondingly with the overall trend. For example, a correlated peak VI value and peak VI standard deviation would mean that the amplitude of the seasonal changes (variance) increases or decreases with the overall trend. This implies that the relative amplitude of seasonal changes is constant over time and the changes seen in variance are related to the trend. In cases where mean and variance are not correlated, an increase in the variance may indicate areas experiencing stress or a significant change.

For each watershed there is a degree of inherent within watershed variability due to varying conditions of species composition, slopes, soils and other factors (Reed et al. 1994). Therefore, differences in the standard deviation from one year to another may be indicative of stressful conditions over the watershed. Each watershed was checked for consistently increasing or decreasing standard deviation of the time integrated VI value, and rate of greenup, and rate of senescence metrics in the four years to identify any stressful situation. Moreover, mean and variance were also checked for dependency. If a consistent decrease or increase in the mean VPM values was seen during the four years from 2000 to 2003 (e.g. time integrated VI value is decreasing), then this VPM correlated to the standard deviation means that change in the metric values is due to the environmental changes from year to year (which affect the whole watershed in more or

less the same manner e.g. high temperature, early greenup and consequently longer length of the growing season, optimum moisture regime etc.). In a case where the mean and standard deviation are not correlated and an increase or decrease is still seen, the situation is considered more serious and may imply a significant landscape change e.g. harvesting, insect attack, drought, flooding, and nutrient depletion in soil, etc. that may affect a portion of the watershed.

The following temporal characterization presents the phenological characteristics and their inter-annual variability for each of the 16 watersheds. The discussion is based on VPMs derived from EVIm approach.

5.3.1 Goose watershed

This is a large burnt watershed dominated by conifer tree species (66%) with a moderate 8% of the watershed area as peatlands (see Table 5-10). The OG date occurred in mid-May with the exception of the year 2000 when it occurred in mid-June. The EG date occurred in September with peak vegetation in late July to early August. A consistent advance and delay trend is seen for the EG and peak dates during the four years: earlier peak and earlier end date, or delayed peak and delayed end date. The watershed exhibits a trend of earlier greenup from 2000 to 2003. OG and EG VI value appear to relate to the OG date for the four years in a way that the later the greenup occurred in a year, the higher the OG and EG VI values were observed. The higher rate of greenup is associated with the lower rate of senescence that tends to maintain a consistent length of growing season during the four years. However, length of growing season in 2000 is much shorter (86 days) when compared to the rest of the years (119 to 123 days).

5.3.2 Sak A watershed

This burnt watershed is the largest and is mainly coniferous (72%) with a moderate area (9%) of the watershed as peatlands (see Table 5-10). The OG date always occurred in mid- to late May except for the year 2000 when it occurred in early June. The EG and peak date occurred in September and July, respectively for all of the four years. A consistent advance and delay trend is seen in OG and peak date. A higher rate of greenup

was associated with a higher rate of senescence that tends to reduce the fluctuation in the length of the growing season over the four years. Length for year 2002 (140 days) is much longer when compared to other years (113 to120 days).

5.3.3 Chickadee watershed

This large watershed is dominated almost equally by the deciduous (27%), conifer (32%) and mixed wood (15%) species with a substantial 21% of the watershed area as peatlands (see Table 5-10). The OG, EG and peak date occurred in mid- to late May, early to late September, and mid-July, respectively during the four years. No consistent advance or delay trend is seen in the OG and EG dates. OG VI value is related to the OG date: the earlier the greenup occurred, the lesser the OG VI value that was observed. Rate of greenup for 2001 is significantly higher (1239) when compared to other years (941 for 2000, 860 for 2002 and 697 for 2003).

5.3.4 Two creek watershed

This large watershed is mainly coniferous (59%) with substantial 17% of the watershed area as peatlands (see Table 5-10). OG, EG and peak date occurred in early to late May, early to late September and mid-July, respectively, during the four years. A consistent advance and delay trend is seen for the OG and peak date. OG and EG VI value is independent of the OG date; VI value fluctuation for this watershed is insignificant, and it can be assumed that whenever the growing season begins in a year, the corresponding greenness value would remain relatively stable. In other words, the average VI threshold value of greenness can be used to roughly determine the OG for each year. The length of the growing season is longer in 2002 (138 days) when compared to other years (115 to 117 days).

5.3.5 Burnt pine watershed

This small burnt watershed is mainly coniferous; 67% of the watershed area is conifer tree species with 21% rangeland and 10% as peatland (see Table 5-10). OG and peak dates occurred in early to late May and early to late July, respectively. An earlier greenup trend is observed from 2000 to 2003. EG date occurred in September and October, resulting in longer length of growing season when compared to other

watersheds, especially the four large ones (Goose, Sak A, Two creek, Chickadee) described above. A consistent delay and advance trend is observed for the EG and peak date. OG and EG VI value is positively correlated to OG and EG date, respectively. As the rate of greenup and senescence are positively correlated, this tends to reduce the length fluctuations over the four years. However, length in year 2002 (150 days) is quite longer than in other years (124 in 2000, 135 in 2001, 123 in 2003). Rate of greenup is much high for 2000 (1102) and 2003 (1238) as compared to 2001 (732) and 2002 (745). Overall, the phenology of this watershed is different than the Goose, Sak A, Chickadee, Two creek and Fireweed watersheds in that the length of the growing season is longer, both OG and EG VI values are dependent on the OG and EG dates, and EG dates occur later in October for 2000 and 2002.

5.3.6 Fireweed watershed

This small watershed is burnt and is mainly coniferous (54%). 32% of the watershed area is rangeland and 13% is peatland (see Table 5-10). The OG date for the year 2000 occurred in mid-June and for 2001 to 2003 it occurred in mid-May. The peak date consistently occurred at the end of July except for the year 2000 when it occurred in mid-August. The rate of senescence for the year 2000 is high (610) when compared to the other years (585 for 2001, 444 for 2002, and 560 for 2003). This caused the EG date to register in the same month (mid-September) for all of the four years. A consistent delay and advance trend is observed for the OG and peak date, and OG and EG dates are unrelated of their corresponding VI values. The length of the growing season is much shorter in 2000 (96 days) than in other years (116 to 123 days) but this did not impact much on the time integrated VI value because of the higher peak VI value in 2000. The time integrated VI value remained relatively stable over the four years.

5.3.7 1A watershed

This small watershed is 81% coniferous and 3.7% of its area is peatland (see Table 5-10). The OG date occurred in early to late May and it's EG was in mid-September except for in 2003 when it occurred in late August. Its peak date occurred in early to late July except in 2001 when it occurred in August. The OG dates are negatively correlated to the EG dates over the four years: the earlier the OG date occurred, the later the end

date appeared, indicating the lengthening of the growing season. The length of the growing season is highly variable between the four years: 100 days in 2000, 126 days in 2001, 135 days in 2002, and 91 days in 2003. The OG date and OG VI values were negatively correlated: an earlier greenup is associated with the higher OG VI values. A higher rate of greenup is associated with a higher rate of senescence. Rate of greenup for the year 2001 is very low (363) as compared to other years (for 2000: 1186, for 2002: 805, and for 2003: 1165). Although time integrated VI remains relatively stable over the four years, the variance is decreasing from 2000 to 2003. This indicates that the 1A watershed was experiencing a stressful situation in 2000 and that the ecosystem functioning was improving from then on. It may also imply that the watershed has gone through significant landscape changes from 2000 to 2003. Phenological response of the 1A is quite different from other watersheds because of the lengthening effect of the growing season, negative correlation between OG date and VI value and decreasing time integrated variance from 2000 to 2003.

5.3.8 Cassidy watershed

This small watershed is dominated equally by conifer, deciduous and mixed woods species: 32% of the land area is deciduous, 28% coniferous and 39% is mixed woods with almost no peatlands (0.15%) in the watershed (see Table 5-10). The OG date occurred in mid- to late May except in the year 2002, when it occurred in late April. The EG and peak date occurred in early to late September and mid-July, respectively. OG and EG dates are negatively correlated, which tends to lengthen the growing season. In this case, however, the lengthening effect is not seen because of the high positive correlation between the rate of greenup and senescence that reduces length fluctuation. EG and peak date are also negatively correlated. The length of the growing season is highly variable among the four years with longest in 2002: for 2000 it is 119 days, for 2001 it is 99 days, for 2002 it is 165 days, and for 2003 it is 113 days. A significant increase in the variance of time integrated VI value, rate of greenup and rate of senescence from the year 2000 to 2001 may indicate that the watershed was experiencing a stressful situation. This effect may be attributed to the variable vegetation composition in the watershed that responds

differently to climatic fluctuations in each of the four years and hence increases the variance over the years. However, this requires further finer-scale investigation.

5.3.9 Kashka watershed

This small watershed is mainly deciduous (41%) with almost an equal population of conifer and mixed wood species (22% coniferous and 27% mixed wood). 5% of the watershed area is peatlands and 4.2% is disturbed by industrial and urban activity (see Table 5-10). The OG dates occurred consistently in early to mid-May except in 2003 when it occurred at the end of April. EG dates are highly variable: for 2000 and 2001 the EG occurred in mid-September while for 2002 and 2003 it occurred in mid- to late August. The peak date occurred in early to late July over all of the four years. A consistent advance and delay trend was observed for the OG and EG, OG and peak, and peak and EG dates. Higher OG VI values were associated with lower EG VI values and vice versa. Higher rate of greenup was coupled with a higher rate of senescence and the length of the growing season for year 2002 (98 days) was much shorter than the length in other years (109 to 115 days).

5.3.10 Millions watershed

This is the smallest watershed of all and is comprised of 40% deciduous, 27% conifer and 25% mixed wood species with 4.25% peatland and 3.1% industrial and urban activity (see Table 5-10). The OG date occurred in early to mid-May and EG date occurred in mid- to late August except in 2000 when it occurred in early September. The peak date occurred in early July for 2000 and 2003 while it occurred in mid- to late June for 2001 and 2002. This watershed has a consistent OG date but an earlier EG and peak date when compared to other watersheds. The OG and EG VI values are unrelated to the OG and EG dates. No consistence advance or delay trend is seen in the OG and EG dates. The length of the growing season is much shorter in 2001 (75 days) compared to other years (109 to 116 days). The standard deviation of the time integrated VI value and rate of senescence decreases while the rate of greenup metric increases from 2000 to 2002.

5.3.11 Mosquito watershed

This small watershed is mainly deciduous (59%) with a small area (2.6%) of peatlands and quite a bit of industrial disturbance (2.6% of the area consists of roads and other related construction) (see Table 5-10). The OG date occurred in mid- to late May except for in 2002 when it occurred in mid-April. The EG date occurred consistently in mid- to late September and the peak date occurred in early to mid-July except for 2002 when it occurred in late June. For earlier peak dates, the EG date tended to occur later. The OG and EG VI values are slightly dependent upon OG and EG dates. The rate of greenup was very high in 2000, 2001 and 2002 (1090, 1619, 1111, respectively) and low in 2003 (807). Overall, this watershed has the highest rates of greenup of all the watersheds. The length of the growing season for year 2002 (164 days) is considerably longer than the other years (128 in 2000, 110 in 2001, and 118 in 2003).

5.3.12 Pierre watershed

This small watershed is slightly more coniferous (48%) than deciduous (36%) with almost no peatlands (0.5%). Industrial activity in the watershed is significant: 3.8% of the area is roads and other related construction (see Table 5-10). The OG dates occurred in mid- to late May except for in the year 2000 when the OG occurred in early June. The EG and peak date occurred in mid- to late September and late July, respectively. The peak date for year 2000, however, occurred in early August. A consistent advance and delay trend is seen in the OG and peak dates. For earlier EG dates and lower OG VI values, the EG VI values were higher. The rate of greenup and the EG VI values were consistent over all of the four years (2000 to 2003). The shortest growing season occurred in the year 2000 (102 days) compared to other years (120 days in 2001, 138 days in 2002, and 125 days in 2003).

5.3.13 Sak B watershed

This small watershed is 38% deciduous, 21% mixed wood and 15% coniferous with the largest area of peatlands (24%) as compared to other watersheds in the area (see Table 5-10). The OG dates consistently occurred in early to late May, the EG dates occurred in late September to early October and the peak dates occurred in late July to

early August. The OG and EG VI values are positively correlated to the OG and EG dates and higher OG VI values are associated with higher EG VI values. The length of the growing season is almost consistent across the four years, and the rate of greenup for 2001 is the highest (1253) compared to other years (730 in 2000, 914 in 2002, and 805 in 2003).

5.3.14 Thistle watershed

This small watershed is mainly deciduous (59%) with 5.2% of the watershed area as peatlands and 4.7% as industrial disturbance (see Table 5-10). The OG and peak dates occurred in early to late May and mid-July, respectively. The EG dates for 2000 and 2002 occurred in September while for 2001 and 2003 they occurred in late August. For earlier OG dates, delayed EG dates were observed but a consistent delay and advance trend was observed for the OG and peak dates. The longest growing season occurred in 2002 (133 days) compared to other years (103 days in 2000, 97 days in 2001, and 89 days in 2003). The rate of greenup and senescence is consistent across all of the years (2000 to 2003).

5.3.15 Toby watershed

This small watershed is dominated by mixed wood (39%) with 26% conifer and 13% deciduous species. The watershed has a large area of peatlands (19%) (see Table 5-10). The OG dates are highly variable for the four years: the end of May in 2000, early June in 2001, the end of April in 2002, and early May in 2003, possibly due to the mixed composition of the watershed. EG and peak dates most often occurred in early to late September and mid- to late July, respectively, though the peak date for 2000 occurs at the beginning of August. The OG and EG VI values are unrelated to their corresponding dates. The longest growing season occurred in 2002 (148 days) compared to other years (116 days for 2000, 104 days for 2001, and 124 days for 2003). A higher rate of greenup is associated with a lower rate of senescence, and the highest rate of greenup is in the year 2001 (1261) in comparison to other years (857 in 2000, 839 in 2002, and 570 in 2003).

5.3.16 Willow watershed

This small watershed is more deciduous (42%) than coniferous (28%) or mixed wood (23%) with 3.4% of the watershed area as peatlands (see Table 5-10). The OG dates occurred in early to late May, the EG dates in early to late September and the peak dates in early to late July. Earlier EG dates are associated with a late peak date and a higher rate of greenup is associated with a lower rate of senescence. The longest growing season is in 2002 (147 days) when compared to other years (123 days in 2000, 125 days in 2001, and 117 days in 2003). The rate of greenup is high and consistent for the years 2000, 2001 and 2002 while for 2003 it is low (743).

While the above inter-annual phenological characterization of each watershed provides mixed results, it describes the vegetation dynamics from year to year in each watershed. A simpler approach to understanding the subtle differences among the watersheds is to eliminate temporal variability from the analysis. In order to do this, the EVIm based VPMs shown in Table 5-2 were first temporally averaged over the four years (2000 to 2003) to come up with a composite response for each of the 16 watersheds. The resulting sample size of 16 observations for each of the 10 VPMs was then correlated to establish relationships among them (i.e. VPMs). In order to check for the most consistent relationship (or any consistent pattern) across the watersheds in these four years, only the significant Pearson correlation coefficients are reported in Table 5-12. Theoretically, the length of the growing season metric should be positively correlated to both of the OG and EG date metrics since length is the difference of the two metrics (OG and EG dates). However, EG date and not the OG date metric was found to correlate positively with the length metric. Moreover, the length of the growing season was also found to positively correlate to the peak date metric. This implies that OG dates were consistent among the 16 watersheds over the four years and both the EG date and peak date metrics exhibits greater variability and sensitivity (when compared to the OG dates) among these watersheds. A positive correlation of 0.54 (see Table 5-12) between the EG date and peak date metrics further suggests that the variation in both of these metrics is consistent.

Table 5-12: Pearson correlation coefficients among the VPMs.

Length vs. EG date	Length vs. OG date	Length vs. peak date	OG vs. peak date	Time int. VI vs. EG date	Rate of senescence vs. EG date	EG date vs. peak date	Onset VI value vs. end VI value	OG date vs. Rt of greenup
0.92	-0.22	0.73	0.76	0.65	0.66	0.54	0.93	-0.52

Likewise, EG and not the OG date metric was found to correlate with the time integrated VI value metric that reinforces the previous finding of a consistent OG date and a variable EG date among the watersheds. A higher rate of senescence was seen for the delayed EG date among the watersheds resulting in a shortening of the length of the growing season. The OG VI value was seen to increase with an increasing EG VI value among the watersheds.

In order to depict a clear picture of how watersheds behave differently from each other in terms of their phenological response, the watersheds were sorted in ascending order based on the temporal average value of each of the 10 VPMs. The results are shown in Table 5-13*a* and 5-13*b*.

Table 5-13*a*: Watersheds arranged in ascending order based on temporal average VPM values.

Onset date		End date		Peak date		Onset value		End value	
Kashka	5/11	Millions	8/22	Millions	6/28	Goose	2456	Goose	2385
Millions	5/11	Kashka	8/29	Mosquito	7/6	Sak B	2559	Fireweed	2521
Cassidy	5/12	Thistle	8/31	Kashka	7/12	Fireweed	2611	Mosquito	2548
Mosquito	5/13	1A	9/8	Chickadee	7/15	Kashka	2754	Kashka	2605
Sak B	5/14	Goose	9/11	Cassidy	7/15	Mosquito	2870	Sak B	2608
Willow	5/15	Chickadee	9/12	Thistle	7/16	Sak A	2945	Willow	2693
Burnt pine	5/15	Cassidy	9/13	Willow	7/17	Two creek	2998	Sak A	2706
Chickadee	5/16	Fireweed	9/14	Burnt pine	7/18	Thistle	3033	Pierre	2774
Two creek	5/17	Two creek	9/15	1A	7/18	Pierre	3035	Two creek	2790
Sak A	5/18	Sak A	9/16	Two creek	7/20	Chickadee	3061	Chickadee	2812
Toby	5/18	Toby	9/17	Sak A	7/21	Willow	3116	Thistle	2839
Thistle	5/19	Pierre	9/18	Toby	7/22	Burnt pine	3138	Burnt pine	2879
1A	5/19	Mosquito	9/19	Sak B	7/25	1A	3147	Toby	2907
Pierre	5/20	Willow	9/19	Pierre	7/26	Toby	3205	1A	3007
Fireweed	5/22	Burnt pine	9/24	Goose	7/28	Cassidy	3419	Cassidy	3116
Goose	5/24	Sak B	9/28	Fireweed	7/29	Millions	3483	Millions	3188

Table 5-13*b*: Watersheds arranged in ascending order based on temporal average VPM values.

Peak value		Length		Time-int.VI		Rt of greenup		Rt of senescence	
Goose	4382	Millions	103	Goose	30668	Pierre	672	Millions	391
Kashka	4479	Thistle	106	Kashka	31758	Goose	699	Kashka	455
Pierre	4577	Goose	110	Fireweed	32090	Millions	726	Goose	507
Fireweed	4601	Kashka	111	Millions	32517	Fireweed	762	Sak A	510
Millions	4647	1A	113	Pierre	33834	Kashka	788	Burnt pine	514
Thistle	4838	Fireweed	116	Thistle	34912	Thistle	806	Chickadee	517
Sak A	4959	Chickadee	120	Sak A	37591	Sak A	810	Mosquito	517
Two creek	5063	Pierre	121	1A	37604	Two creek	833	Pierre	522
1A	5071	Two creek	121	Two creek	38113	1A	880	1A	530
Chickadee	5120	Sak A	122	Chickadee	38225	Toby	882	Two creek	532
Toby	5209	Toby	123	Toby	38483	Sak B	925	Thistle	536
Mosquito	5215	Cassidy	124	Mosquito	38702	Chickadee	934	Fireweed	550
Willow	5373	Willow	128	Willow	40856	Burnt pine	954	Willow	555
Sak B	5404	Mosquito	130	Sak B	41108	Willow	1012	Toby	568
Burnt pine	5495	Burnt pine	133	Cassidy	42329	Cassidy	1061	Sak B	588
Cassidy	5719	Sak B	138	Burnt pine	43863	Mosquito	1157	Cassidy	626

Moreover, in order to investigate the linkages between the land use in the FORWARD watersheds and the response of the VPMs, the EVIm based temporally averaged VPMs were correlated to each watershed's percent species composition (Table 5-10) and only the significant correlations are reported in Table 5-14.

Table 5-14: Pearson correlation coefficients between the 4 year temporal average of VPMs versus the watersheds' landuse composition.

OG date vs. % conifer	OG date vs. % deciduous	OG date vs. % mixed woods	EG date vs. % industrial	St_dev of OG vs. % industrial	St_dev of EG vs. % industrial	St_dev of peak vs. % Industrial	St_dev of length vs. % industrial
0.58	-0.48	-0.62	-0.5	0.69	0.49	0.57	0.64

Key points emerging from the phenological characterization of individual watersheds and the analysis of temporally averaged VPMs are:

- a consistent decrease in variance of the time integrated VI values (variance being uncorrelated to the mean value), from 2000 to 2003 in the 1A watershed may indicate

that the watershed is recovering from a stressful situation, possibly a landscape change;

- a significant increase in the variance of time integrated VI values, rate of greenup and rate of senescence from the year 2000 to 2001 in the Cassidy watershed may indicate that the watershed was subjected to a stressful situation during this time period;

- the Thistle and Pierre watersheds have the most consistent rate of greenup and senescence across all of the years (2000 to 2003);

- an early OG date was found to be associated with a higher rate of greenup that, theoretically, should contribute to the lengthening of the growing season. However, a delayed EG date coupled with a higher rate of senescence appeared to offset this effect;

- little variability is seen in the OG dates when compared to the EG and peak dates of the watersheds. This suggests that EG and peak dates are more sensitive indicators of the watershed conditions than the OG dates;

- while the OG date is positively correlated (0.58) to the percent conifer species in the watersheds, it is negatively correlated to the percent deciduous and mixed wood species (-0.48 for deciduous and -0.62 for mixed wood);

- while EG dates for the watersheds are not correlated to any of the percent conifer, deciduous or mixed wood species, they are negatively correlated (-0.5) to the industrial and urban activity in the watersheds. The watersheds with greater industrial and urban disturbance, such as Kashka, Thistle and Millions, are seen to have earlier (and highly variable in four years) EG dates (Table 5-13*a*). Given that length of the growing season is highly correlated (0.92) to the EG date (the later the EG date, the longer the growing season), industrial disturbance seems to shorten the length of the growing season;

- temporal average of the standard deviation of OG, EG, peak date and the length of the growing season are positively correlated to the industrial and urban activities in the watersheds (0.69, 0.49, 0.57 and 0.64, respectively); and finally,

- no significant correlation was found between the percent peatland in the watersheds and any of the VPMs, possibly because the VIs cannot differentiate between different underlying soil types.

5.4 Environmental Control of Vegetation Phenology

To assess the environmental control of vegetation phenology, daily meteorological data (temperature and precipitation) from 2000 to 2003, collected at the Whitecourt airport weather station, were correlated to the MODIS EVI and NDVI data. The coefficients are reported in Table 5-15 and Table 5-16. Daily Mean Temperature (MT), Total Rain (TR), Total Snow (TS) and Total Precipitation (TP) values were averaged over the 16-day composite period to align with the MODIS mean EVI and NDVI values that were computed over the whole FORWARD study area. The choice of these meteorological factors is based partly on the availability of the data and partly on the findings of previous research (see Literature Review II section under Phenology: Indicator of Stress and Measure of Ecosystem Resilience), which has indicated that temperature, photoperiod and moisture availability play a major role in the photosynthetic activity of the deciduous and coniferous forested landscape (Reed et al. 1994).

In the year 2000, the Whitecourt airport weather station received 567.6 mm of total precipitation, of which 21.3% occurred as snow; in the year 2001, total precipitation was 471.4 mm, of which 22.2% occurred as snow. These two years (2000 and 2001) can be considered as the "wet" years compared to the year 2002, when total precipitation was 365.3 mm, of which 54.2% occurred as snow and the year 2003, when total precipitation was 407 mm, of which 62.2% occurred as snow.

Table 5-15 and 5-16 suggest that EVI and NDVI are most highly correlated to the mean 16-day temperature, followed by the mean 16-day total rain when compared to the mean 16-day total precipitation for each of the four years, 2000 to 2003. The only exception to this trend is seen for the NDVI in the years 2000 and 2001 when NDVI

versus TR correlation is very low, possibly because these two years received a large amount of rainfall when compared to the years 2002 and 2003. The correlation between the VIs (NDVI and EVI) and the mean 16-day total snow values is negative and low (as expected). EVI and the product of MT and TR were found to be more correlated than the simple EVI and MT or EVI and TR. This effect could not be seen for the NDVI, where almost 80% (for the year 2003) of the data variation is explained by the MT alone. EVI and NDVI were also correlated to the product of MT and TP but little to no improvement was noticed in the coefficients.

Table 5-15: Pearson correlation coefficients between EVI and meteorological data.

Year	EVI vs. MT	EVI vs. TR	EVI vs. TS	EVI vs. TP	EVI vs. (MT x TR)	EVI vs. (MT x TP)
2000	0.74	0.70	-0.48	0.62	0.76	0.76
2001	0.70	0.61	-0.45	0.55	0.62	0.63
2002	0.74	0.81	-0.49	0.33	0.89	0.83
2003	0.70	0.76	-0.55	0.14	0.85	0.73
All four years	0.72	0.60	-0.51	0.42	0.63	0.65

Table 5-16: Pearson correlation coefficients between NDVI and meteorological data.

Year	NDVI vs. MT	NDVI vs. TR	NDVI vs. TS	NDVI vs. TP	NDVI vs. (MT x TR)	NDVI vs. (MT x TP)
2000	0.80	0.54	-0.52	0.42	0.55	0.61
2001	0.75	0.31	-0.32	0.26	0.32	0.33
2002	0.79	0.78	-0.57	0.25	0.74	0.79
2003	0.90	0.80	-0.60	0.19	0.77	0.82
All four years	0.81	0.46	-0.55	0.26	0.45	0.52

MT = Mean Temperature, TR = Total Rain, TS = Total Snow, and TP = Total Precipitation.

From the above results, it appears that in the wet years (2000 and 2001) the ecosystem had abundant moisture available and hence the photosynthetic activity was not limited by the TR. However, in the dry years (2002 and 2003) the moisture availability seems to slightly limit or to control the photosynthetic activity in the ecosystem and thus the correlation coefficients are high for both NDVI. This effect is not so pronounced in the EVI correlations, possibly due its lower sensitivity. The single best predictor of

vegetation dynamics in the FORWARD study area seems to be the mean temperature. Thus, based on this relationship, time-series plots and regression equations (with scatter plots) were established between the MT and EVI and MT and NDVI over the four years (2000 to 2003) and are presented in Figures 5-4 to 5-9. These plots were also established for each of the years 2000 to 2003, separately, to provide for a clear insight into the yearly variation and are presented in Appendix C in Figures C-1 to C-16.

EVI behaves differently than NDVI when the EVI scatter and time-series plots are closely observed. For all of the years, EVI exhibits a lower correlation with MT than the NDVI (see Table 5-15 and 5-16). Specifically, EVI does not correlate well to the below-zero extremely cold temperatures from January to April: for decreasing temperatures, the EVI values do not fall (decrease) correspondingly (see the dotted circles on the EVI time-series plot). This behavior can be attributed to the abnormally high response of EVI algorithm to the snow covered ground. Moreover, the scatter plot for below 5 °C temperature versus EVI for 2000 to 2003 depicts no correlation between EVI and MT. It is only after snow melt (above 5 °C) that the EVI and MT relationship is established (see Figure 5-8).

NDVI, on the other hand, registers extremely low vegetation values and thus corresponds well to the MT variation. Comparing the NDVI time-series plots among different years, the year 2001 plot exhibits a unique behavior (see the dotted circle on the NDVI time-series plot). Raw NDVI values are much higher in winter when compared to the winter values in other years. This can be attributed either to the faulty raw NDVI values in the data or that the landscape was not completely covered with snow, causing the NDVI to register higher values during the winter. The latter explanation can be supported by the fact that the year 2001 had the highest winter temperatures compared to the other years (2000, 2002 and 2003) that may have caused intermittent snow melt in the study area. This explanation can also be used to explain the 'funneling' effect caused by the inconsistent, high and low NDVI values for the extremely low temperatures (-20 °C to +5 °C) seen in Figure 5-7. The intermittent snow melt in the study area might have caused the NDVI to register very high (for the bare ground) and very low (for the snow) values, resulting in almost no correlation. It is only after snow melt (above 5 °C) that the

NDVI and MT relationship is established (see Figure 5-9). A more flat and weaker R^2 NDVI versus above 5 °C MT relationship in Figure 5-9 when compared to the EVI versus above 5 °C MT relationship in Figure 5-8 clearly portrays the saturation aspect of NDVI algorithm in high biomass regions such as FORWARD study area.

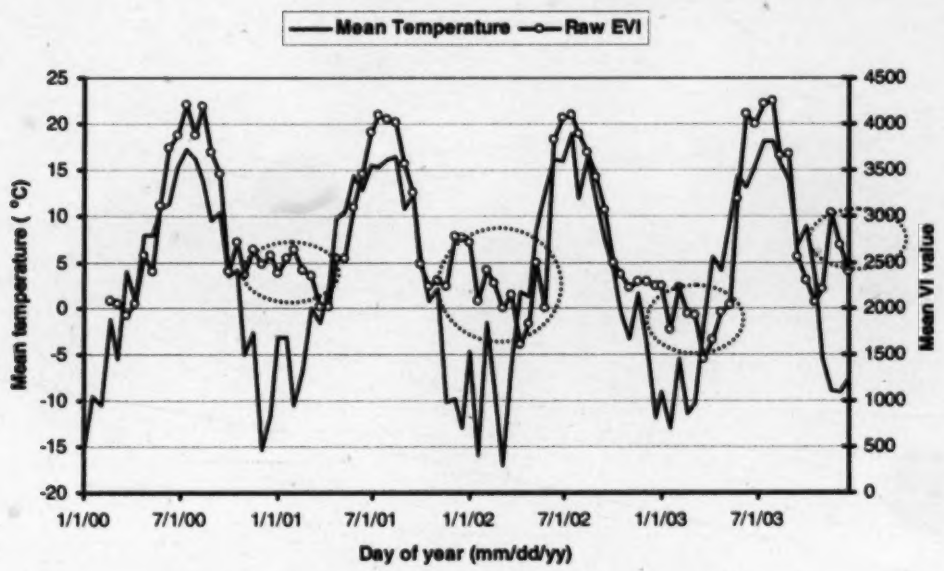

Figure 5-4: Time-series plot of mean temperature and EVI over 2000 to 2003.

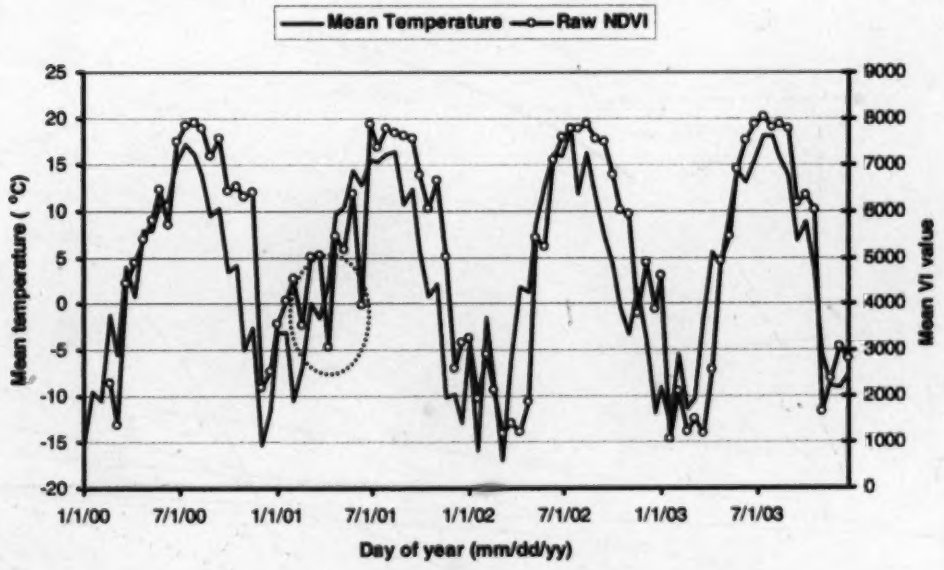

Figure 5-5: Time-series plot of mean temperature and NDVI over 2000 to 2003.

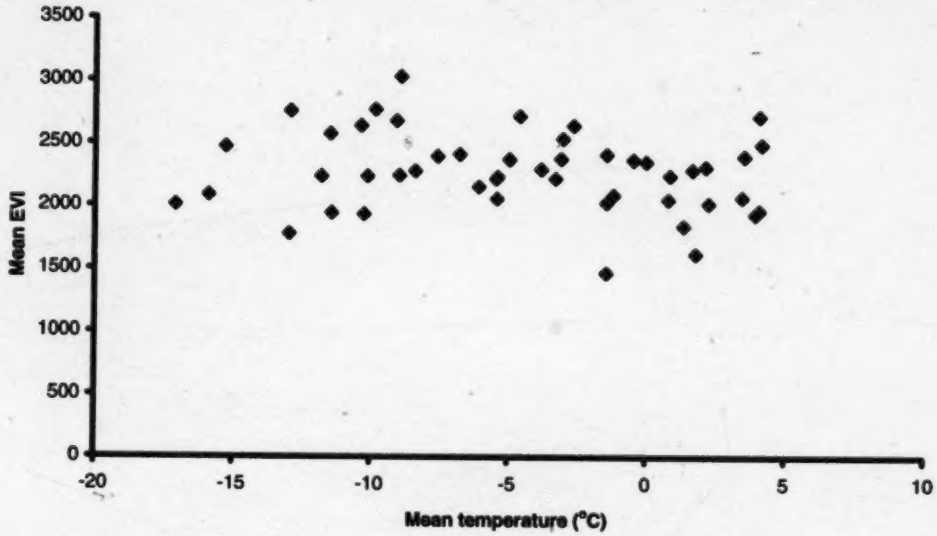

Figure 5-6: Scatter plot for below 5 °C temperature versus EVI for 2000 to 2003.

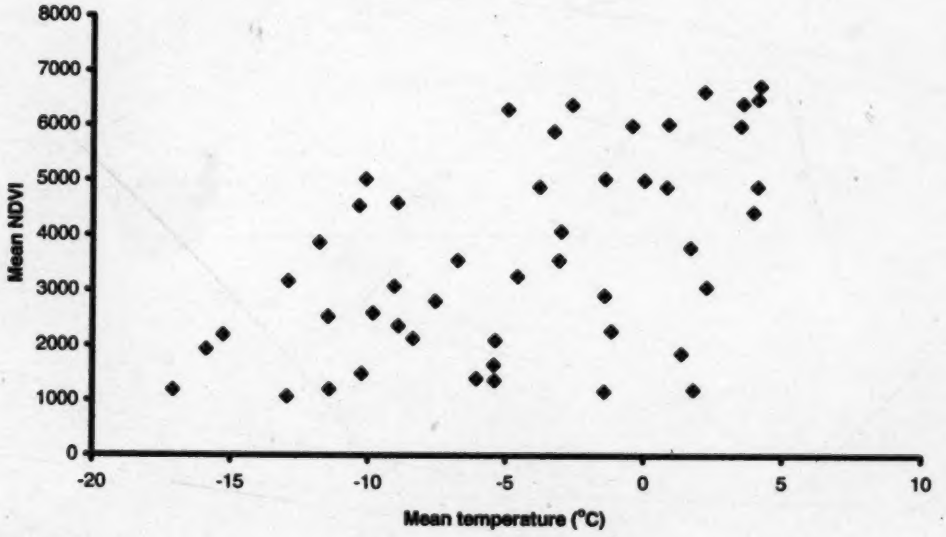

Figure 5-7: Scatter plot for below 5 °C temperature versus NDVI for 2000 to 2003.

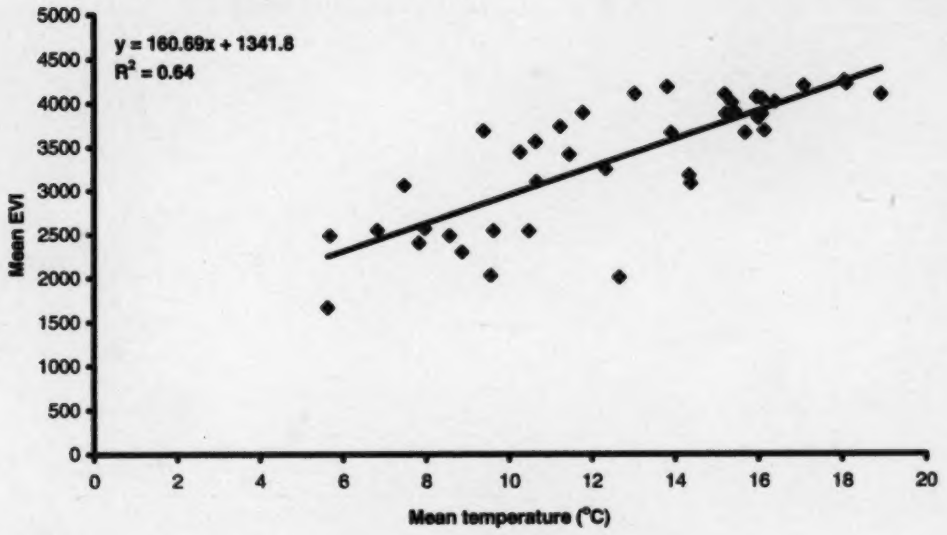

Figure 5-8: Scatter plot for above 5 °C temperature versus EVI for 2000 to 2003.

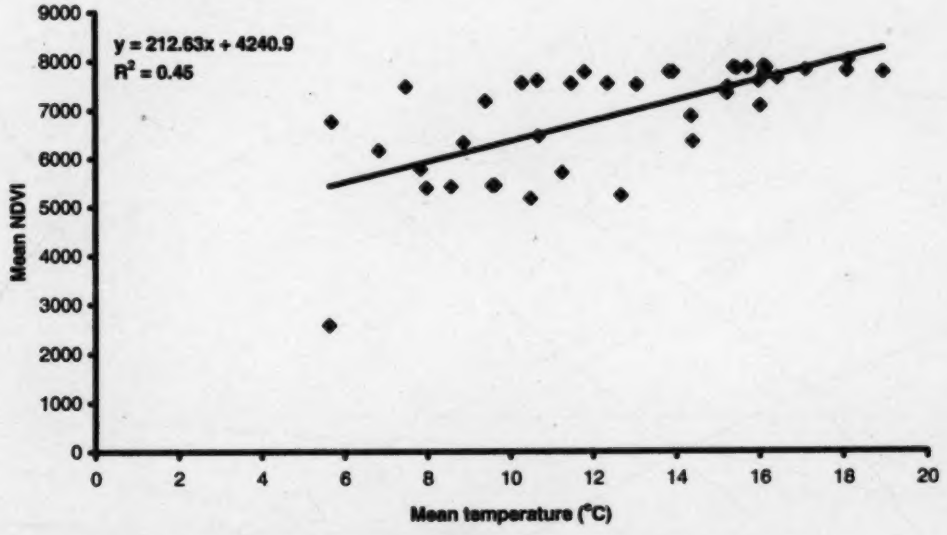

Figure 5-9: Scatter plot for above 5 °C temperature versus NDVI for 2000 to 2003.

5.5 Biomass Accumulation in the Study Area

The time integral of the NDVI over the growing season has been correlated with Net Primary Production (NPP) (Running and Nemani 1988; Prince 1991; Justice et al. 1985; Tucker and Sellers 1986). NPP approximately equals the actual amount of organic matter created by green plants i.e. the biomass accumulation. NDVIm based time integrated VI values for each of the 16 watersheds have been reported in Table 5-4.

Growing Degree Days (GDD) above 0 °C and 5 °C for 2000 to 2003 recorded at the Whitecourt airport weather station is provided in Table 5-17. The GDD above 0 °C for the years 2000 to 2003 compare well to the longer-term mean GDD value of 2319.1, which is computed using data of at least 15 years from 1971 to 2000 for this weather station (Environment Canada 2003*c*). However, this is not the case for the GDD above 5 °C value: the longer-term mean of 1289.1 (Environment Canada 2003*c*) is much lower than the GDD above 5 °C values for the years 2000 to 2003. This discrepancy can be attributed to error in the meteorological data. Table 5-17 presents time integrated VI values computed over the whole FORWARD area based on EVIm and NDVIm approaches.

Table 5-17: Time integrated VI values for NDVIm and EVIm approaches and GDD in 2000 to 2003.

Year @ approach	Time integrated VI	GDD above 0 °C	GDD above 5 °C
2000 NDVIm	88302.33	2180.2	2063.6
2000 EVIm	37613.90		
2001 NDVIm	96149.63	2422.1	2272.4
2001 EVIm	35960.84		
2002 NDVIm	85882.88	2165.5	2032.6
2002 EVIm	38756.25		
2003 NDVIm	89259.14	2428	2327.1
2003 EVIm	35464.39		

NDVIm time integrated VI values in four years (2000 to 2003) are positively correlated to the GDD above 0 °C and above 5 °C (0.73 and 0.64, respectively) that indicates that biomass accumulation is dependent on the availability of heat over the same year. The EVIm time integrated VI values are perfect-negatively correlated (-0.96

and -0.97, respectively) that does not make sense. However, little is known about the EVIm derived time integrated VI value.

The years 2001 and 2003 had the highest GDD (2422 and 2428, respectively) compared to 2000 and 2002 (2180 and 2165, respectively). The highest time integrated NDVI value of 96149 (Table 5-17) is seen for the year 2001, followed by the year 2000, when it was 88302. Both of these years were quite wet because the total rain recorded in 2000 and 2001 was 484.1 mm and 393.9 mm, respectively, compared to 2002 and 2003, when it was 204.8 mm and 208.7 mm, respectively. Moreover, year 2001 also had a higher GDD. A higher time integrated NDVI value can be seen for the dry year 2003 than for the dry year 2002, possibly because of the higher GDD in the year 2003. It seems that time integrated NDVI value (biomass accumulation) is a function of GDD and moisture availability over the same year.

5.6 Discussion

Results from the VPMs show a strong coincidence with ground based phenological observations near the study area. These ground based phenological observations (Table 5-9), while limited to only year 2001 and thus certainly not a complete validation dataset, are extremely valuable and reliable since individual observers have reported these blooming events.

When analyzing the results, it is important to consider that the mean and standard deviation of VPMs were derived for only vegetated pixels within each watershed, ignoring all of the zero pixels that represent non-vegetated elements of the landscape (water bodies, roads, burnt forest, and other industrial activities). These zero values were not included in the mean VPM calculation because they would bias the mean towards the lower end. As a result, timings of major events would be seen much earlier than what is shown now, depending on how many zero pixels are present within each watershed. Removing zero pixels from the mean VPM computation essentially means that the effect of non-vegetated pixels on the phenological behavior of each watershed has been removed. This, of course, is desirable when the objective of the study relates only to the vegetation portion of the landscape such as when we must accurately determine the OG

and EG dates of the vegetation in order to model the impact of global warming or to compute GDD, for example. However, if the objective of the study is to investigate the response of a function in which the non-vegetated portions of the landscape do play a role e.g. seeking interrelationships between vegetation parameters (such as VPMs) and water quality and quantity variables (nutrient export to the stream, flow generated, etc.), the zero pixels must be included in the mean VPM computation. To assess the effect of non-vegetated elements of the landscape on the phenological behavior of FORWARD watersheds, mean VPMs computed, excluding zero pixels, were subtracted from mean VPMs including zero pixels. The difference tables for EVIm and NDVIm approaches are presented in Appendix C as Table C-5 and C-6, respectively. For ease of interpretation, temporal averages over the four years (2000 to 2003) for these difference tables were also calculated and watersheds were arranged in ascending order for each VPM. The averaged tables are presented in Appendix C as Table C-7 and C-8, and provide an idea of the watersheds that are most affected by removing the zeroes from the mean VPM computation. The zero effect is investigated for only EVIm and NDVIm approaches because the effect was found to be the same for the EVIm, EVIz and NDVIm, NDVIz approaches.

A major source of subjectivity introduced in this research is watershed delineation, which can significantly impact mean VPM values. Some landscape changes (mostly harvest) have also occurred which were not updated in the AVI used in this study. Moreover, the four years data available from the MODIS VI dataset is inadequate for accurately characterizing the inter-annual variability of vegetation dynamics in the study area. The low temporal resolution (16-days) of the time-series VI data further limited the utility of this analysis. The lack of watershed level meteorological data also limited inter-comparison efforts, and the inter-annual variability of VPMs over the study area could not be explicitly stated. Results must be analyzed carefully since patterns of associations have been reported which, instead of deductively advocating causation, point towards factors that probably play an important role in the function of interest and hence need further investigation at a finer scale.

Chapter 6

Conclusions and Recommendations

MODIS VI temporal profiles were used to compare inter-annual vegetation seasonal and phenologic activity, peak greenness, length of growing season, onset of greenness and senescence, biomass accumulation and derivative rates of greenup and senescence on a watershed level in the Boreal forest landscape. This research attempts to characterize vegetation dynamics in terms of VPMs that have the potential to evaluate variability or stability (Reed et al. 1994) of watershed phenology, to provide an early warning of ecosystem stress, to support management decisions related to maintaining forest productivity and to serve as sustainability criteria that the forestry industry can use to report to regulatory agencies.

The following conclusions are drawn from the analysis:

- statistically insignificant differences are found between the Zhang and Zhang modified approach based VPMs for the MODIS 4 year data (2000 to 2003);
- statistically significant differences are found between the EVI and NDVI based VPMs for the MODIS 4 year data (2000 to 2003);
- onset of greenup dates for the Zhang approach qualitatively appear earlier than the onset dates for the Zhang modified approach when both are compared to ground based observations;
- EVIm based VPMs coincide well with ground based budburst observations near the study area when compared to the NDVIm based VPMs;

- while EVIm based onset of greenup corresponds to the canopy greenup, the NDVI based onset of greenup corresponds to the snowmelt event and under-storey greenup;

- MODIS NDVI and EVI data acquired over the FORWARD study area is found to have a weak per-pixel correlation and the effect of data treatment on the correlation coefficient is mixed. This weak correlation is contrary to the statements in the relevant literature;

- a consistent decrease in variance of the time integrated VI values from 2000 to 2003 in the 1A watershed may indicate that the watershed is recovering from a stressful situation, possibly a landscape change;

- a higher percentage of conifer species tends to delay the onset of the growing season in the watershed, while a higher percentage of deciduous and mixed wood species favors earlier onset. Overall, the correlation among the VPMs and between the VPMs and watershed land use percentages are found to be consistent with the relevant literature;

- variability in the OG dates across FORWARD 16 watersheds is much less than the variability in the EG and peak dates. This suggests that the EG and peak dates are more sensitive indicators of watershed conditions than the OG dates and may serve as the sustainability indicators of a watersheds' health;

- increasing industrial activities (such as road construction and other related disturbances) in a watershed appear to shorten the length of the growing season by favoring an early end of the greenup date. Moreover, an increase in the variance of the EVIm derived OG, EG, peak date and the length of the growing season metrics is seen for increasing industrial activities;

- biomass accumulation appears to be a function of GDD and the moisture availability over the same year;

- the NDVI based time integrated VI value metric performed consistently with the statements of previous researchers.

- while the NDVIm time integrated VI value represents biomass accumulation, the EVIm time integrated VI value metric remained elusive, and difference in response of the two metrics could not be well characterized;

- the MODIS 16-day mean EVI and NDVI values, computed by spatially averaging over all the FORWARD study area, were found to positively correlate to the 16-day mean temperature recorded at Environment Canada's Whitecourt airport weather station i.e. the mean temperature is a very good predictor of the EVI and vice versa.

- correlation coefficients between NDVI and the total rain recorded at the Whitecourt weather station indicates that in wet years (2000 and 2001), the vegetation activity was independent of the total rain: the ecosystem was not limited by the moisture availability since plenty of moisture was available. This effect is less pronounced for the EVI versus total rain coefficients, possibly due to lower sensitivity of the EVI; and finally,

- the EVI did not correlate well to extreme below-zero temperatures when compared to the NDVI.

The results, while positive in some respects, indicate no general trend from 2000 to 2003 over the FORWARD study area. Moreover, the analysis of spatial variability of these trends did not reveal any substantial watershed differences.

The results above elaborate the different responses of the two VIs (EVI and NDVI) in characterizing vegetation dynamics. EVI is reported to be more useful for upper canopy investigation in primarily forested landscapes; NDVI, on the other hand, has well-established and well-characterized responses for studying biomass accumulation. However, both the indices have marked shortcomings in characterizing the vegetation covered with snow. NDVI exhibits extremely low and EVI exhibits extremely high vegetation values for the snow presence on the ground. The answer to the question of

whether EVI or NDVI is best suited to characterize landscape phenology depends on the goals of the researcher. Factors such as canopy closure, land use land cover type, and presence of snow, etc. must be considered before deciding which VI to use. The results must then be interpreted within the context of defined study objectives, acknowledging the differences between the two VIs.

These results have considerable implications for natural resource monitoring. As management perspectives are shifting away from riparian vegetation analysis to larger landscape investigations, many countries, including Canada, are developing national-scale monitoring protocols for the monitoring of natural resources (EMAN 2003) that require broad scale screening indicators as surrogates of ecological health (Griffith et al. 2002). The Ontario Ministry of Natural Resources, Forest Research Institute (1997) reported that "measurable indicators of forest condition are urgently needed in Ontario and elsewhere." The Ministry had previously initiated the Bioindicators of Forest Sustainability project, which attempted to develop a Forest Condition Rating (FCR) system that uses RS spectral features to identify forests on a quantitative scale from "healthy" to "stressed". This research, hence, is another effort to explore the potential of RS VPMs to serve as screening indicators for use in such monitoring programs as Environment Canada's Ecological Monitoring and Assessment Network (EMAN).

Identification of peak photosynthetic levels in the growing season has considerable implications for evapotranspiration studies (Senay and Elliott 2000) whereby temporal variability in water use patterns throughout the growing season can be marked. The VPMs provide a temporal distribution of the vegetation cycle and hence, the nitrogen, phosphorus, and nutrient uptake cycles can be adjusted using the VPM information for each year. For example, water use and nutrient uptake is expected to be a maximum at the peak photosynthetic activity and lowest at the end of the growing season. Moreover, the precipitation intercepted and the subsequent runoff generated before and after the peak photosynthetic activity in a watershed can be expected to carry different levels of nutrient loading. The implications of phenological information for hydrological modeling, however, have not been completely explored yet. Even the most comprehensive hydrology models, such as the Soil Water Assessment Tool (SWAT) by the USDA,

assume an average or optimum uptake of nutrients by the vegetation throughout the growing season (or in a year). The scarce incorporation of vegetation phenology information in ecosystem and hydrological simulation models to date, may be attributed not so much to the absence of interest as to the problems associated with acquiring this kind of information (White et al. 1997). Imaging frequency and synoptic coverage of advanced satellite sensors have finally made it possible to extract the phenological timing and growth phases of earth's vegetation.

The results also have implications for water quality studies. Johnson et al. (1997) summarized many studies that relate water quality with land use land cover (LULC). Particularly, nitrogen and phosphorus have been found to have strong relationships with LULC (Lowrance et al. 1985; Bolstad and Swank 1997). However, LULC is a temporally static characterization and does not account for seasonal, inter-annual or directional changes (Hobbs 1990) as VPMs do. Griffith (2002) found that VPMs were more highly correlated to water quality parameters than simple LULC proportions. VPMs can also be correlated with insect emergence time for pest control purposes and can be used to indicate the optimal times to apply herbicides and insecticides.

This research is unique because it attempts to investigate satellite derived phenology (VPMs) on a watershed scale and a small area (740 km^2) and with a 250 m resolution pixel. Scale differences may have an impact (1 km versus 500 m versus 250 m spatial resolution) on the findings but investigating scale dependencies of VPMs was beyond the scope of this study. Previous research has focused on a large area (global focus) for the VPM extraction on the 'land cover level' with a spatial resolution of 1 km or more, and reported that the results are consistent with the expected phenological response of various land cover types. VPM information, however, is not well suited for land use land cover (LULC) classification, and different land cover types may have the same phenological response depending on various factors. Since VIs are correlated to photosynthetic activity (for the Boreal biome where moisture is not a limiting factor), VPMs provide information about the physiological rather than the structural condition of the watersheds. This photosynthetic activity for deciduous canopies is highest in newly expanded, high chlorophyll leaves, and much reduced in older, low chlorophyll leaves

that are approaching dormancy (Reich et al. 1995). Moreover, for all species, photosynthetic activity is sensitive to age, soil type, drought and flooding, genetic variation within the same species, and many other factors (see Literature Review II under Phenology: Indicator of Stress and Measure of Ecosystem Resilience). Therefore, different percentages of canopy cover (White et al. 1997) and LULC proportions (e.g. a deciduous stand and a conifer stand) may be associated with the same photosynthetic potential.

Many researchers, including Reed et al. (1994), typically employed Loveland et al. (1993) classification with 159 land cover types. White et al. (1999), in contrast, included only six land cover types based on Nemani and Running (1995) purely RS classification, in their phenology model development, and argued that the inclusion of detailed land cover classes might render more accuracy but would require a large amount of ancillary information that is difficult or impossible to acquire for 'large areas', making regular updates at global scale impractical. This research is based on the idea that the phenological characterization of a small area can be monitored over a few years, and that the detailed ancillary (land cover, species and meteorological) information, with regular updates, can be acquired to accurately understand spatial and inter-annual variation and the factors responsible for this variation. The main caveat in this research is the small sample size of the data (four years) to calculate the correlation coefficients that were used to characterize inter-annual variability of the phenological responses. Use of longer term time-series VI data (as it becomes available) with more sophisticated quality control, such as the one recommended by Didan and Yin (2002), and the inclusion of detailed, species level land cover information beyond the conifer, deciduous and mixed woods resolution, might allow for more accurate inter-watershed differences characterization. Moreover, RS snow cover data must be employed in conjunction with the EVI and NDVI data to capture the vegetation dynamics in the snow covered areas.

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Appendix A: MODIS Data Validation

Table A-1: Summary of data sets used in MODIS VI validation efforts (Huete et al. 1999).

Campaign/Data Set	Dates	Sensors	Purpose
Chile - GLCTS (Test Sites)	September, 1996	Cimel, Exotech, (Ground and Light Aircraft)	•VI-saturation test (rainforest) •VI-baseline test (hyper-arid) •VI-threshold test (arid/semiarid) •VI-biophysical (all)
LTER Sites, U.S.A. (Long-Term Ecological Research)	Ongoing, 1992 - (Annual and Seasonal)	TM, AVHRR, ASAS, MAS	•VI-seasonality, compositing •Field correlative measures - biophysical - phenologic
SCAR-B (Brasil)	August to September, 1995	MAS, AVIRIS, Exotech, Cimel	•VI-smoke analysis •VI-saturation (bandwidths) •VI-biophysical •Continuity analysis (AVHRR, MODIS) (Tropical forest/cerrado)
HAPEX-Sahel (Niger, Africa)	August to October, 1992	ASAS, TM, Exotech, Cimel	•VI-biophysical, angular compositing threshold (Semiarid)
OTTER Transect (Oregon)	1992	ASAS, TM	•VI-biophysical, angular, compositing saturation (Forests)
Monsoon '90	August to September, 1990 September, 1991 Seasonal, 1992	ASAS, AVIRIS, TM, Exotech, (Air, Ground), Spectron	•VI-angular, compositing threshold •VI-seasonality, biophysical (semiarid)
FIFE (Kansas, USA)	May to September, 1987 and July to August, 1989	ASAS, TM	•VI-biophysical, angular, compositing (grassland)
BOREAS (Canada)	August to September, 1995	ASAS, TM	•VI-biophysical, angular, smoke, compositing (boreal forest)
Global-TM/AVHRR GLCTS Pathfinder	1985 to Present	TM, AVHRR	•VI intercomparisons (global) •VI-compositing
MAC (Maricopa Agricultural Center, Arizona)	1986 to Present	TM, Exotech, Sun Photometer, BRDF	•VI-seasonal; biophysical, angular •Dry-wet backgrounds

Command used for File-level (metadata) quality check

Command prompt:\ Dowloaded Raw data>read_meta –meta=
AUTOMATICQUALITYFLAG, QAPERCENTMISSINGDATA,
QAPERCENTOUTOFBOUNDSDATA, QAPERCENTCLOUDCOVER,
QAPERCENTINTERPOLATEDDATA , QAPERCENTGOODQUALITY,
QAPERCENTOTHERQUALITY, QAPERCENTNOTPRODUCEDCLOUD,
QAPERCENTNOTPRODUCEDOTHER, EVI250M16DAYQCLASSPERCENTAGE,
QAPERCENTPOORQ250MOR500M16DAYEVI, PGEVERSION,
SCIENCEQUALITYFLAG, SEAPROCESSED

Command used for Pixel-level (SDS) quality check

Command prompt:\Dowloaded Raw data>unpack_sds_bits -of=unpack_1 -sds="250m 16 days NDVI Quality","250m 16 days EVI Quality" -bit=0-1,2-5,6-7,11-12 MOD13Q1.A2000049.h11v03.004.2002359025816.hdf

Appendix B: Overview of MODIS QA Approach

Table B-1: Descriptions of the VI QA SDS (MLST 2004).

Bit No.	Parameter Name	Bit Comb.	Description
0-1	VI Quality (MODLAND Mandatory QA Bits)	00	VI produced with good quality
		01	VI produced but with unreliable quality and thus examination of other QA bits recommended
		10	VI produced but contaminated with clouds
		11	VI not produced due to bad quality
2-5	VI Usefulness Index	0000	Perfect quality (equal to VI quality = 00: VI produced good quality)
		0001	High quality
		0010	Good quality
		0011	Acceptable quality
		0100	Fair quality
		0101	Intermediate quality
		0110	Below intermediate quality
		0111	Average quality
		1000	Below average quality
		1001	Questionable quality
		1010	Above marginal quality
		1011	Marginal quality
		1100	Low quality
		1101	No atmospheric correction performed
		1110	Quality too low to be useful
		1111	Not useful for other reasons
6-7	Aerosol Quantity	00	Climatology used for atmospheric correction
		01	Low
		10	Intermediate
		11	High
8	Atmosphere Adjacency	0	(No) No adjacency correction performed
		1	(Yes) Adjacency correction performed
9	Atmosphere BRDF Correction	0	(No) No atmosphere-surface BRDF coupled correction performed
		1	(Yes) Atmosphere-surface BRDF coupled correction performed
10	Mixed Clouds	0	(No) No mixed clouds
		1	(Yes) Possible existence of mixed clouds
11-12	Land/Water Mask	00	Ocean/inland water, Shallow ocean, Moderate and continental ocean, Deep ocean, Deep inland water
		01	Coastal region, Ocean coastlines, lake shorelines, Shallow inland water

		10	Wetland Ephemeral water
		11	Land
13	Snow/Ice	0	(No) No snow/ice
		1	(Yes) Possible existence of snow/ice
14	Shadow	0	(No) No shadow
		1	(Yes) Possible existence of shadow
15	Compositing Method	0	BRDF composite method used for compositing
		1	Constraint view angle MVC (CV-MVC) method used for compositing

Table B-2: Relationship between the MODLAND mandatory per-pixel QA bits and QA metadata objects (MLST 2004).

VI Quality Bit Combination	Corresponding QA Metadata Object
00: VI produced, good quality	QAPercentGoodQuality
01: VI produced, unreliable quality	QAPercentOtherQuality
10: VI produced, contaminated with cloud	QAPercentNotProducedCloud
11: VI not produced due to bad quality other than cloud	QAPercentNotProducedOther

Table B-3: VI Usefulness Index scaling method for the MOD13Q1 product (MLST 2004).

Parameter Name	Condition	Score
Aerosol Quantity	If aerosol climatology was used for atmospheric correction (00)	2
	If aerosol quantity was high (11)	3
Atmosphere Adjacency Correction	If no adjacency correction was performed (0)	1
Atmosphere BRDF Correction	If no atmosphere-surface BRDF coupled correction was performed (0)	2
Mixed Clouds	If there possibly existed mixed clouds (1)	3
Shadow	If there possibly existed shadow (1)	2
View zenith angle (q_v)	If $q_v > 40^\circ$	1
Sun zenith angle (q_s)	If $q_s > 60^\circ$	1

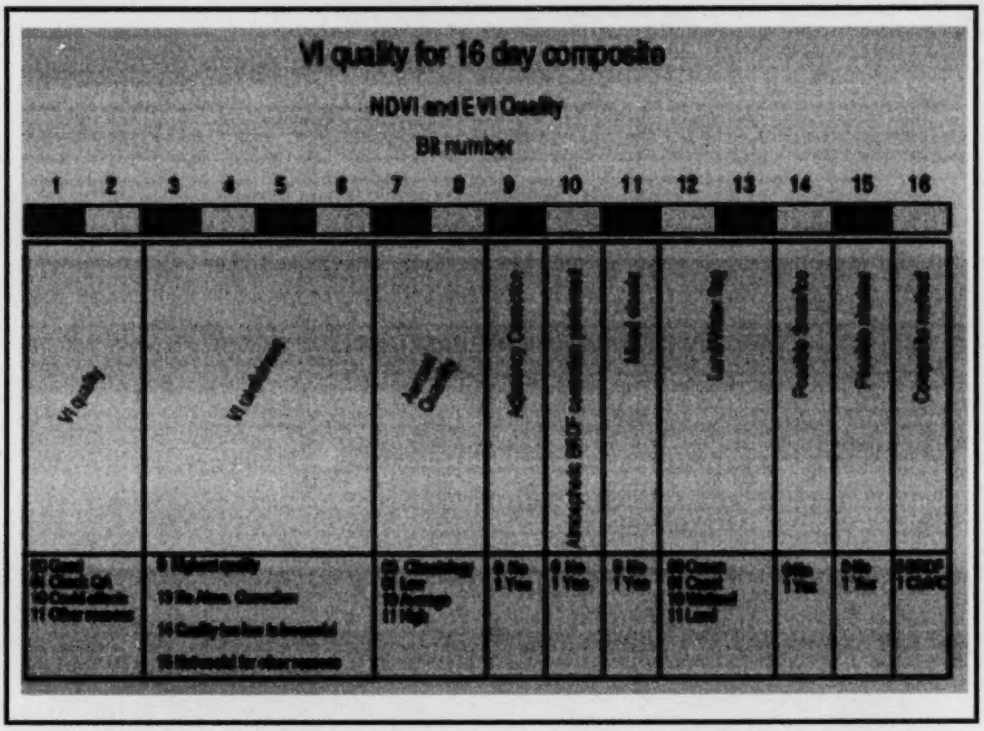

Figure B-1: MODIS VI QA SDS bit map. Source: MODIS Land Science Team (MLST) (2004).

Table B-4: List of the QA metadata objects for the MOD13Q1 product (MLST 2004).

Object Name	Object Type	Group Name	Description	Level
AutomaticQuality Flag	ECS Mandatory QAFlags, Text	InventoryMetadata in *CoreMetadata.0*	Result of an automatic quality assessment performed during product generation Valid value: "Passed", "Suspect", or "Failed"	Per-SDS, Per-Tile
AutomaticQuality FlagExplanation	ECS Mandatory QAFlags, Text	InventoryMetadata in *CoreMetadata.0*	Explanation of the result of the automatic quality assessment Valid value: Up to 255 characters Sample value: "Run was successful But no land data found/processed"	Per-SDS, Per-Tile
OperationalQuality Flag	ECS Mandatory QAFlags, Text	InventoryMetadata in *CoreMetadata.0*	Result of an manual, non-science quality assessment performed by production facility personnel after production Valid value: "Passed", "Suspect", "Failed", "Inferred Passed", "Inferred Failed", "Being Investigated", or "Not Being Investigated"	Per-SDS, Per-Tile

OperationalQuality FlagExplanation	ECS Mandatory QAFlags, Text	InventoryMetadata in *CoreMetadata.0*	Explanation of the result of the manual, non-science quality assessment Valid value: Up to 255 characters Sample value:	Per-SDS, Per-Tile
ScienceQuality Flag	ECS Mandatory QAFlags, Text	InventoryMetadata in *CoreMetadata.0*	Result of an manual, science quality assessment performed by science computing facility personnel after production Valid value: "Passed", "Suspect", "Failed", "Inferred Passed", "Inferred Failed", "Being Investigated", or "Not Being Investigated"	Per-SDS, Per-Tile
ScienceQuality FlagExplanation	ECS Mandatory QAFlags, Text	InventoryMetadata in *CoreMetadata.0*	Explanation of the result of the manual, science quality assessment Valid value: Up to 255 characters Sample value:	Per-SDS, Per-Tile
QAPercent InterpolatedData	ECS Mandatory QAStats, Numeric	InventoryMetadata in *CoreMetadata.0*	Percentage of interpolated data in the tile Valid value: 0~100 Sample value: 12	Per-SDS, Per-Tile
QAPercent MissingData	ECS Mandatory QAStats, Numeric	InventoryMetadata in *CoreMetadata.0*	Percentage of missing data in the tile Valid value: 0~100 Sample value: 8	Per-SDS, Per-Tile
QAPercent OutOfBoundData	ECS Mandatory QAStats, Numeric	InventoryMetadata in *CoreMetadata.0*	Percentage of data in the tile of which values are out of a valid range Valid value: 0~100 Sample value: 2	Per-SDS, Per-Tile
QAPercent CloudCover	ECS Mandatory QAStats, Numeric	InventoryMetadata in *CoreMetadata.0*	Percentage of cloud covered data in the tile Valid value: 0~100 Sample value: 15	Per-SDS, Per-Tile
QAPercent GoodQuality	MODLAND Mandatory, Numeric	InventoryMetadata in *CoreMetadata.0*	Percentage of data produced with good quality in the tile Valid value: 0~100 Sample value: "4"	Per-Tile
QAPercent OtherQuality	MODLAND Mandatory, Numeric	InventoryMetadata in *CoreMetadata.0*	Percentage of data produced with unreliable quality in the tile Valid value: 0~100 Sample value: "56"	Per-Tile
QAPercent NotProducedCloud	MODLAND Mandatory, Numeric	InventoryMetadata in *CoreMetadata.0*	Percentage of data produced but contaminated with clouds in the tile Valid value: 0~100 Sample value: "32"	Per-Tile
QAPercent NotProducedOther	MODLAND Mandatory, Numeric	InventoryMetadata in *CoreMetadata.0*	Percentage of data not produced due to bad quality in the tile Valid value: 0~100 Sample value: "8"	Per-Tile

NDVI500M16DAY QCLASS PERCENTAGE	VI Product Specific, Numeric	InventoryMetadata in *CoreMetadata.0*	Percentage of NDVI data produced with good quality in the tile Valid value: 0~100 Sample value: "4"	Per-Tile
EVI500M16DAY QCLASS PERCENTAGE	VI Product Specific, Numeric	InventoryMetadata in *CoreMetadata.0*	Percentage of EVI data produced with good quality in the tile Valid value: 0~100 Sample value: "4"	Per-Tile
QAPERCENT POORQ 500M16DAYNDVI	VI Product Specific, Numeric	ArchivedMetadata in *ArchiveMetadata.0*	Summary statistics (% frequency distribution) of the NDVI usefulness index over the tile Valid format: (N, N, N, N, N, N, N, N, N, N, N, N, N, N, N, N), where N = 0~100 Sample value: (4,0,0,0,44,6,18,15,5,0,0,0,0,0,0,8)	Per-Tile
QAPERCENT POORQ 500M16DAYEVI	VI Product Specific, Numeric	ArchivedMetadata in *ArchiveMetadata.0*	Summary statistics (% frequency distribution) of the NDVI usefulness index over the tile Valid format: (N, N, N, N, N, N, N, N, N, N, N, N, N, N, N, N), where N = 0~100 Sample value: (4,0,0,0,44,6,18,15,5,0,0,0,0,0,0,8)	Per-Tile

Appendix C: Analysis of VPMs

Table C-1: Standard deviation of EVIz based VPMs for 2000-2003 for 16 watersheds.

Watersheds	Year	Onset date	End date	Peak date	Onset value	End value	Peak value	Len-gth	Time-int.VI	Rt of greenup	Rt of senescence
1A	2000	37	46	36	756	949	1367	46	11811	756	547
	2001	47	35	26	669	512	673	46	10086	333	200
	2002	35	40	35	909	567	884	41	9626	447	159
	2003	31	31	31	699	623	737	27	6372	614	410
Burnt pine	2000	28	24	27	771	500	905	32	9065	643	411
	2001	27	19	25	690	509	512	32	7793	446	146
	2002	42	48	36	792	1035	694	55	12240	679	187
	2003	40	21	16	644	772	607	41	8791	651	120
Cassidy	2000	30	44	25	731	1018	933	40	10318	525	224
	2001	27	35	26	875	665	1247	47	11151	742	481
	2002	42	34	41	794	679	1048	52	12274	840	197
	2003	39	14	30	831	577	1006	38	10223	497	280
Chickadee	2000	41	42	28	735	802	1047	44	10568	572	385
	2001	31	41	24	797	710	928	44	10482	590	239
	2002	44	47	39	1147	712	1004	48	11076	675	278
	2003	41	30	33	846	706	776	38	8418	487	362
Fireweed	2000	38	37	24	725	704	724	39	7202	378	401
	2001	39	46	31	1350	656	981	44	7790	670	396
	2002	31	39	34	1733	687	805	40	8625	445	182
	2003	27	40	29	594	772	830	37	6496	382	375
Goose	2000	48	46	23	911	908	721	34	7393	457	307
	2001	56	40	24	1030	771	766	53	8011	410	276
	2002	38	49	35	1385	892	931	35	8010	584	270
	2003	32	47	26	965	1134	701	45	6080	382	396
Kashka	2000	43	44	24	764	596	580	56	10114	259	243
	2001	39	60	25	701	585	924	51	9730	480	299
	2002	48	70	35	1016	939	910	40	7632	422	267
	2003	42	41	35	1039	712	1022	41	8318	672	253
Millions	2000	32	50	30	614	677	602	55	11963	525	379
	2001	30	39	11	584	483	403	46	9423	463	249
	2002	57	54	49	804	531	1449	60	12679	971	163
	2003	56	36	39	587	432	992	52	10267	748	204
Mosquito	2000	35	40	21	705	832	594	40	9524	445	218
	2001	19	33	14	884	487	525	33	8967	501	258
	2002	49	54	37	1081	932	754	55	11505	717	169
	2003	38	29	23	936	659	830	35	7505	400	367
Pierre	2000	45	55	31	655	912	937	50	11180	448	477
	2001	56	37	34	798	552	860	66	13024	453	286
	2002	42	47	42	1616	659	723	45	10663	544	253
	2003	35	42	38	543	747	1081	42	8670	610	1077

Sak A	2000	39	38	30	800	736	997	43	10947	581	402
	2001	37	34	26	838	607	917	40	8479	485	266
	2002	41	47	40	1120	724	985	48	11309	623	222
	2003	35	33	28	812	728	774	38	8155	559	313
Sak B	2000	22	31	24	891	747	788	35	8639	293	263
	2001	26	32	24	608	799	716	36	9633	482	214
	2002	38	44	28	1691	943	736	44	8495	476	174
	2003	27	40	20	1143	1106	737	44	6608	369	252
Thistle	2000	48	47	32	1004	893	1191	49	12113	577	580
	2001	48	49	35	883	648	1439	51	12021	673	352
	2002	47	43	48	1180	699	1262	54	13144	720	356
	2003	45	34	34	954	687	927	34	9148	525	258
Toby	2000	30	34	27	481	506	946	35	9344	364	587
	2001	38	31	25	634	748	1023	38	10213	619	151
	2002	47	36	44	1252	486	1334	46	12430	607	242
	2003	40	28	30	885	458	811	39	7638	512	829
Two creek	2000	43	36	29	767	810	1164	44	10922	635	459
	2001	42	31	27	738	604	858	43	9799	466	219
	2002	41	40	39	1221	717	1007	47	11330	733	243
	2003	37	32	31	806	716	878	40	9105	668	278
Willow	2000	34	34	27	845	690	1053	38	11151	573	291
	2001	42	30	28	856	624	1304	43	10579	755	294
	2002	41	40	33	1416	696	1022	46	11374	749	181
	2003	40	27	28	1035	699	1069	35	9012	670	288

Table C-2: Standard deviation of EVIm based VPMs for 2000-2003 for 16 watersheds.

Watersheds	Year	Onset date	End date	Peak date	Onset value	End value	Peak value	Len-gth	Time-int.VI	Rt of greenup	Rt of senescence
1A	2000	36	42	37	790	973	1397	46	11899	1152	759
	2001	44	32	26	559	477	679	44	9948	431	241
	2002	34	35	34	1129	534	881	35	8377	741	205
	2003	30	30	29	908	565	740	28	7410	660	412
Burnt pine	2000	22	21	27	857	495	935	32	9375	880	421
	2001	26	17	25	576	525	510	32	7553	662	152
	2002	43	32	34	715	746	644	51	10616	720	199
	2003	40	21	25	742	586	621	42	8915	712	493
Cassidy	2000	27	38	24	694	815	948	39	10468	821	254
	2001	24	40	26	906	757	1256	52	12508	1495	861
	2002	43	29	40	1257	599	1058	51	12100	988	250
	2003	39	13	31	888	530	996	41	10676	671	283
Chickadee	2000	35	38	28	694	715	1046	41	9973	935	494
	2001	28	41	23	894	703	917	44	10575	1062	348
	2002	44	41	38	1266	633	980	46	10758	856	302
	2003	41	28	33	875	669	784	39	8606	621	438
Fireweed	2000	37	33	23	677	675	721	37	7351	702	487
	2001	34	44	28	1432	662	940	39	7202	944	398

	2002	33	36	34	1471	599	796	39	8229	812	191
	2003	31	37	28	1009	922	835	34	5984	710	403
Goose	2000	45	43	23	900	736	708	31	7185	707	380
	2001	45	38	23	1016	722	751	45	7678	591	303
	2002	38	46	33	1370	839	894	34	7791	706	315
	2003	32	43	26	1114	1048	685	40	6167	415	436
Kashka	2000	37	40	23	708	873	561	50	9075	337	262
	2001	35	59	25	671	527	912	50	9945	1072	399
	2002	47	68	37	1136	854	915	43	8319	744	397
	2003	43	39	37	896	665	1068	42	8278	1047	252
Millions	2000	30	44	31	586	520	625	48	10482	615	502
	2001	26	41	10	714	520	398	47	9682	678	327
	2002	56	45	49	1141	433	1213	47	9817	893	124
	2003	56	34	39	857	423	991	56	10937	734	195
Mosquito	2000	32	35	21	687	657	596	36	8670	864	279
	2001	16	36	14	777	645	523	37	9827	892	362
	2002	48	43	39	1037	700	753	48	9992	1257	173
	2003	37	27	23	1204	520	830	34	7273	487	367
Pierre	2000	38	51	31	610	959	915	46	10277	915	637
	2001	54	33	34	802	524	864	64	12720	837	362
	2002	41	35	37	1644	588	706	40	9949	572	195
	2003	35	39	37	638	766	1070	40	8406	670	1098
Sak A	2000	35	35	30	795	686	999	40	10428	896	458
	2001	33	32	25	851	620	909	38	8347	767	320
	2002	41	42	39	1147	638	966	46	10842	878	259
	2003	34	32	27	1014	711	756	37	8133	662	346
Sak B	2000	17	26	24	777	656	798	30	8338	446	284
	2001	22	29	24	660	716	711	35	9654	774	256
	2002	36	40	28	1671	899	741	39	7907	751	263
	2003	26	32	20	1269	1177	760	38	6373	591	251
Thistle	2000	42	44	32	961	745	1193	40	10381	840	707
	2001	45	47	34	956	657	1434	50	11734	1093	442
	2002	46	39	48	1166	694	1253	50	12152	1133	347
	2003	43	32	34	884	624	929	35	9430	653	331
Toby	2000	26	31	26	565	400	990	37	9990	749	632
	2001	36	29	25	701	629	1061	42	10865	1033	249
	2002	46	26	44	1349	546	1356	49	13116	1151	261
	2003	41	27	27	928	805	804	39	7530	415	844
Two creek	2000	35	33	29	718	754	1161	41	10456	1002	582
	2001	39	30	26	811	604	853	42	9725	758	267
	2002	41	34	37	1355	633	984	44	10932	935	306
	2003	37	30	31	945	705	856	39	9175	715	358
Willow	2000	28	31	26	883	665	1032	34	10136	925	378
	2001	38	30	27	819	715	1299	44	10614	1355	408
	2002	40	34	32	1479	618	1014	42	10609	1081	187
	2003	39	26	26	1330	602	1028	34	8833	657	359

Table C-3: Standard deviation of NDVIz based VPMs for 2000-2003 for 16 watersheds.

Watersheds	Year	Onset date	End date	Peak date	Onset value	End value	Peak value	Len-gth	Time-int.VI	Rt of greenup	Rt of senescence
1A	2000	51	24	39	1830	1559	606	48	22864	281	880
	2001	60	32	37	1716	2133	520	70	29856	384	997
	2002	13	35	34	1462	1574	488	34	15618	414	472
	2003	17	36	21	953	1999	507	38	17545	223	296
Burnt pine	2000	53	19	31	1670	2031	386	44	20087	218	594
	2001	37	36	34	1454	1671	323	52	23180	410	878
	2002	16	46	24	1010	1612	359	42	17974	305	361
	2003	13	39	27	951	1764	325	38	12677	257	264
Cassidy	2000	63	14	28	1848	1244	217	51	24031	226	482
	2001	64	31	41	1867	1552	162	71	28486	434	635
	2002	21	33	43	1859	1612	330	39	18319	354	486
	2003	18	19	24	1349	1506	209	29	10099	244	205
Chickadee	2000	58	26	33	2109	1890	467	52	22998	335	549
	2001	47	23	46	1725	2037	555	52	21650	479	1069
	2002	19	28	30	1483	1700	452	32	14556	378	565
	2003	17	19	28	1147	1593	424	27	11013	277	447
Fireweed	2000	41	32	21	1440	1281	800	41	16305	288	357
	2001	60	36	33	1542	1721	689	54	20893	228	1197
	2002	19	54	20	529	1643	669	46	17461	448	274
	2003	22	13	16	1296	1299	565	28	8963	235	171
Goose	2000	38	38	28	1737	1515	893	44	21160	370	553
	2001	59	27	31	2035	1559	708	52	19605	307	728
	2002	15	48	28	1480	1800	767	40	19630	365	645
	2003	17	18	22	1575	1944	643	26	13785	295	311
Kashka	2000	55	26	29	1833	1697	415	54	21176	269	435
	2001	50	24	57	1827	2053	420	50	18845	454	1599
	2002	18	22	33	701	1883	441	32	13484	297	886
	2003	15	15	26	1182	1254	305	20	11180	223	513
Millions	2000	40	5	40	1901	1450	279	44	20896	310	468
	2001	43	3	45	1351	1858	393	50	20842	402	863
	2002	29	9	48	1548	1208	317	27	11729	554	504
	2003	15	8	32	911	1128	249	16	6089	235	486
Mosquito	2000	44	21	29	2327	1415	537	46	21930	310	294
	2001	44	21	30	2491	2054	569	55	22992	421	274
	2002	25	36	33	1913	2433	765	39	20479	367	363
	2003	19	19	27	1635	1772	624	31	16175	252	406
Pierre	2000	61	20	33	1554	1543	755	53	26347	248	452
	2001	58	24	53	1954	2110	646	58	21579	299	901
	2002	17	42	23	1476	1273	462	36	15099	352	333
	2003	18	12	20	1258	1478	470	24	9065	166	458
Sak A	2000	48	30	32	1926	1793	775	50	24407	337	519
	2001	61	30	40	1773	2002	685	58	25036	326	1058
	2002	20	36	29	1554	1756	655	35	17783	392	577
	2003	16	24	25	1237	2102	680	29	15671	289	359
Sak B	2000	22	28	21	1439	1796	408	36	14530	252	269
	2001	48	38	36	1715	1865	571	54	21631	326	1528

	2002	12	24	34	668	1737	794	27	13975	334	1160
	2003	23	20	19	1373	2035	645	31	11071	231	237
Thistle	2000	39	23	43	2070	1573	577	42	21480	372	696
	2001	52	24	49	1953	2003	702	53	24696	454	1187
	2002	15	25	35	1905	2070	691	30	15335	413	693
	2003	19	16	29	1261	1401	525	27	13488	369	381
Toby	2000	41	27	38	1879	2192	704	51	21699	458	314
	2001	44	27	54	1504	2151	512	49	19822	361	935
	2002	14	46	18	1404	1321	362	34	13724	323	166
	2003	16	13	25	1295	1048	370	21	6694	215	314
Two creek	2000	55	28	30	2034	1873	488	49	21634	333	538
	2001	54	21	40	1888	2205	495	52	22690	356	1069
	2002	19	28	23	1542	1851	398	32	14183	341	338
	2003	16	20	28	1261	1617	458	24	12045	316	378
Willow	2000	53	28	30	2128	1719	576	47	21152	299	412
	2001	57	28	35	2136	2006	521	54	23087	349	913
	2002	18	35	33	1640	2155	658	40	17241	465	622
	2003	19	22	21	1343	1615	503	34	14967	247	254

Table C-4: Standard deviation of NDVIm based VPMs for 2000-2003 for 16 watersheds.

Watersheds	Year	Onset date	End date	Peak date	Onset value	End value	Peak value	Length	Time-int.VI	Rt of greenup	Rt of senescence
1A	2000	47	22	40	1301	1149	603	49	24351	358	917
	2001	55	20	40	1658	2015	517	59	25286	309	1248
	2002	9	32	34	1666	1492	511	27	14301	423	506
	2003	14	23	21	1057	1690	521	28	13314	248	261
Burnt pine	2000	37	13	31	1240	1843	388	38	17462	335	588
	2001	32	27	43	1506	1865	319	50	22413	314	1117
	2002	13	30	24	1573	1318	347	31	13205	268	343
	2003	11	25	27	1390	1394	320	27	7466	291	284
Cassidy	2000	43	7	29	1375	1188	230	35	16734	205	492
	2001	59	20	43	1738	2006	156	60	22990	494	698
	2002	21	22	42	2100	1692	335	36	16317	437	499
	2003	15	15	24	1374	1499	209	23	9034	301	226
Chickadee	2000	48	18	33	1546	1590	455	45	20818	376	529
	2001	40	18	49	1619	2009	561	45	19449	720	1163
	2002	15	19	32	1704	1547	464	24	12408	476	677
	2003	13	13	28	1317	1465	425	18	9514	344	460
Fireweed	2000	35	26	21	992	1163	804	39	16277	379	345
	2001	54	33	32	1345	1737	707	49	19788	208	1109
	2002	14	32	22	604	1541	651	27	12421	367	337
	2003	23	8	16	2077	1146	565	25	8369	234	171
Goose	2000	29	32	28	1346	1352	880	41	21165	481	578
	2001	43	24	32	1920	1506	732	40	17818	312	791
	2002	11	36	29	1751	1720	784	31	17206	378	756
	2003	17	13	22	1822	1840	642	22	13234	321	335
Kashka	2000	50	13	29	1662	1396	386	49	20853	281	425
	2001	42	20	62	1715	2043	432	47	17559	752	1827

	2002	12	14	34	943	1736	452	18	10244	325	898
	2003	12	10	26	1401	1071	305	14	9509	254	496
Millions	2000	34	3	40	603	1204	276	36	17975	222	449
	2001	43	3	45	1275	1751	380	48	20098	448	852
	2002	29	7	47	1504	1086	315	28	11725	347	486
	2003	11	5	32	1141	1128	249	11	5063	261	484
Mosquito	2000	30	19	29	2142	1163	530	33	19047	348	287
	2001	37	19	35	2495	1892	550	50	22575	459	494
	2002	26	22	33	2040	2099	745	33	20149	404	337
	2003	14	11	27	1887	1663	624	16	14052	301	405
Pierre	2000	48	15	37	1327	1278	755	40	21742	342	589
	2001	52	20	55	1856	2264	669	52	20254	340	1078
	2002	12	33	23	1862	1175	442	32	13998	310	370
	2003	16	9	21	1170	1226	470	20	8284	162	422
Sak A	2000	40	24	31	1495	1486	771	46	23590	398	488
	2001	53	24	42	1643	1918	693	50	22772	401	1106
	2002	16	27	30	1810	1663	684	25	15532	484	652
	2003	14	16	25	1533	1836	678	22	13578	312	373
Sak B	2000	18	19	21	1170	1638	405	28	12350	355	254
	2001	39	31	37	1556	1994	597	49	19906	365	1571
	2002	10	16	34	1299	1598	805	21	12717	410	1142
	2003	18	12	19	1514	1543	645	20	9569	291	233
Thistle	2000	33	21	43	1786	1379	573	36	19666	419	733
	2001	48	17	52	1983	1944	635	47	22977	460	1269
	2002	12	17	36	1944	1946	693	21	13717	455	701
	2003	16	11	29	1481	1306	525	19	11705	606	381
Toby	2000	26	12	38	1171	1702	728	32	15084	747	479
	2001	37	23	55	1436	2080	534	45	18490	582	932
	2002	10	39	18	1646	1253	334	30	10615	307	162
	2003	13	9	25	1494	1048	370	17	6100	246	307
Two creek	2000	46	22	31	1681	1641	478	43	19505	427	560
	2001	49	16	42	1801	2068	504	47	21270	400	1160
	2002	15	19	24	1715	1691	402	23	11973	391	378
	2003	14	13	28	1371	1504	459	19	10753	375	371
Willow	2000	36	24	28	1640	1686	555	38	18211	357	393
	2001	50	20	37	2011	1916	534	50	21552	377	1056
	2002	15	22	34	1614	1968	652	27	13691	592	612
	2003	16	16	21	1515	1523	507	26	13082	336	278

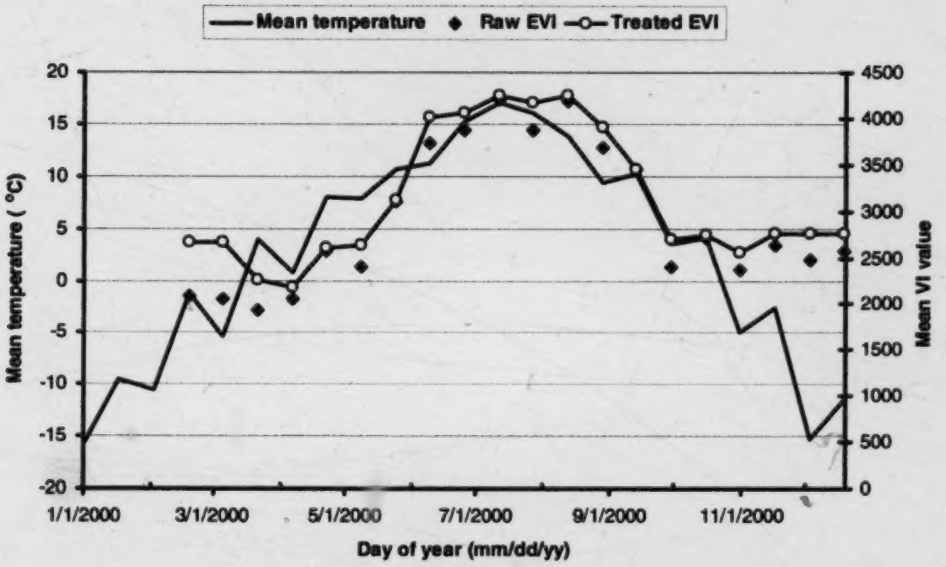

Figure C-1: Time series plot of mean temperature and EVI for the FORWARD study area in 2000.

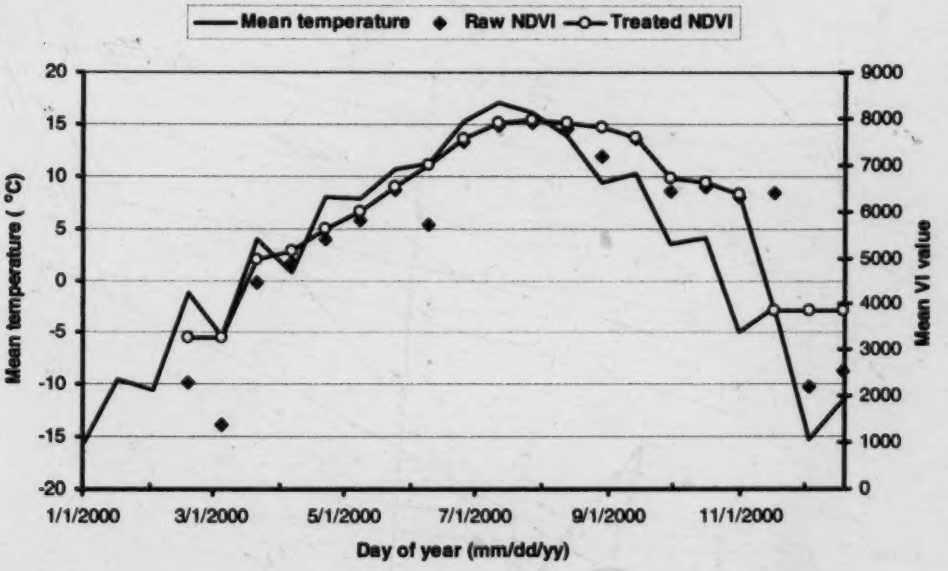

Figure C-2: Time series plot of mean temperature and NDVI for the FORWARD study area in 2000.

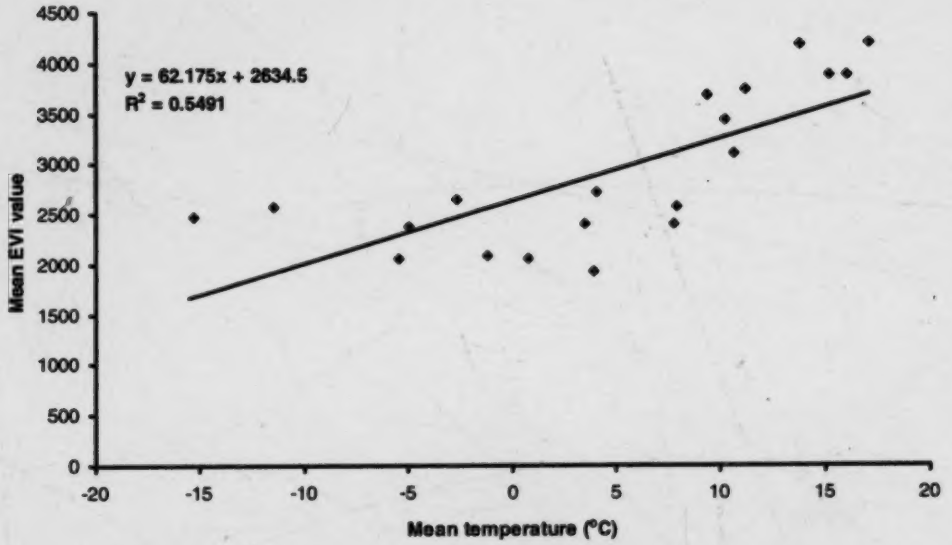

Figure C-3: Mean temperature versus mean EVI for the FORWARD study area in 2000.

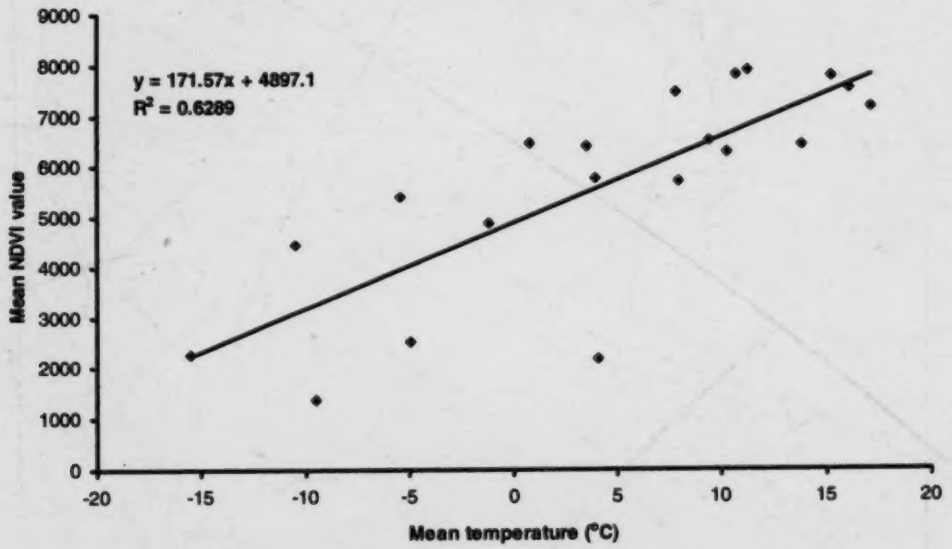

Figure C-4: Mean temperature versus mean NDVI for the FORWARD study area in 2000.

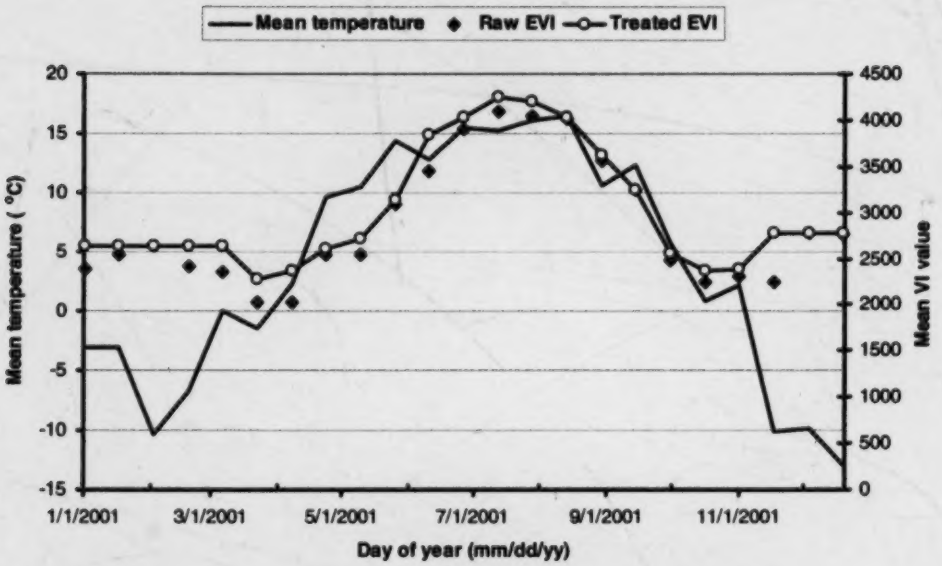

Figure C-5: Time series plot of mean temperature and EVI for the FORWARD study area in 2001.

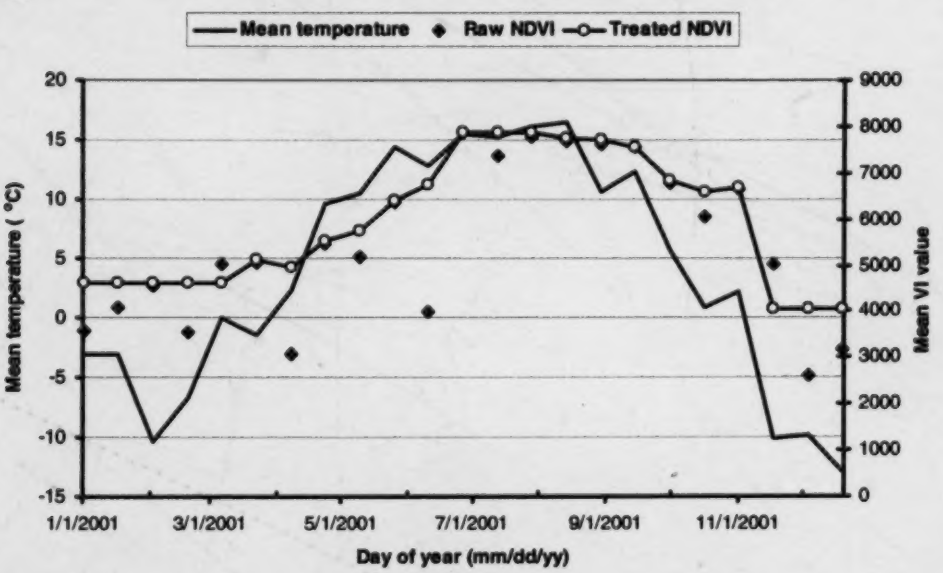

Figure C-6: Time series plot of mean temperature and NDVI for the FORWARD study area in 2001.

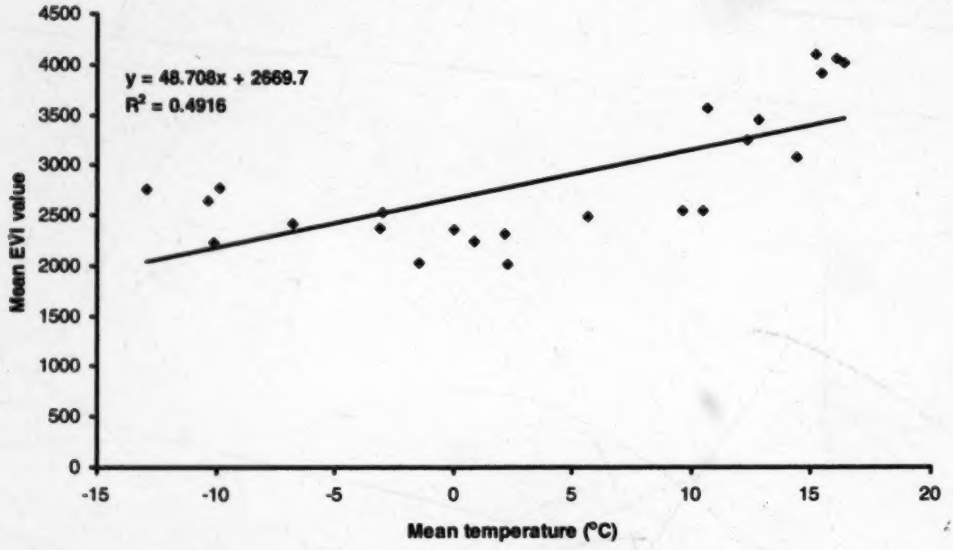

Figure C-7: Mean temperature versus mean EVI for the FORWARD study area in 2001.

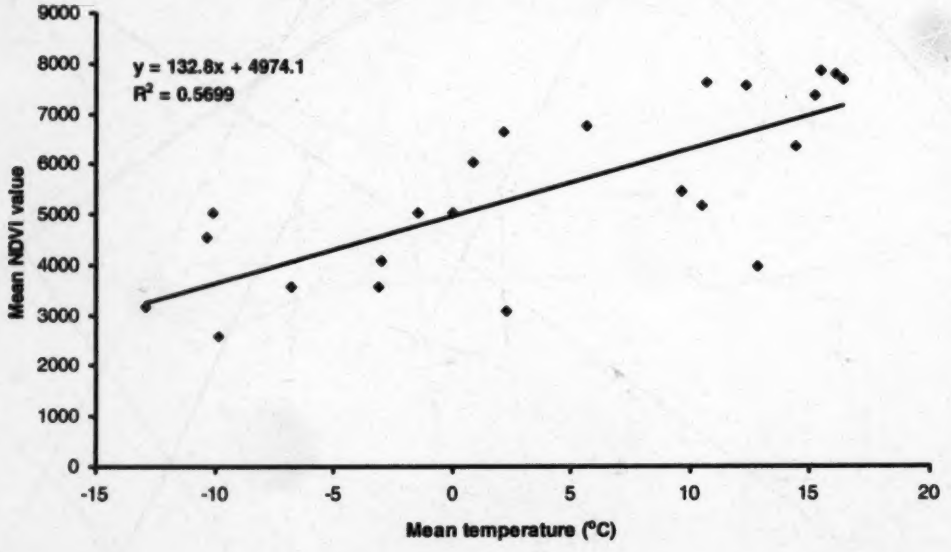

Figure C-8: Mean temperature versus mean NDVI for the FORWARD study area in 2001.

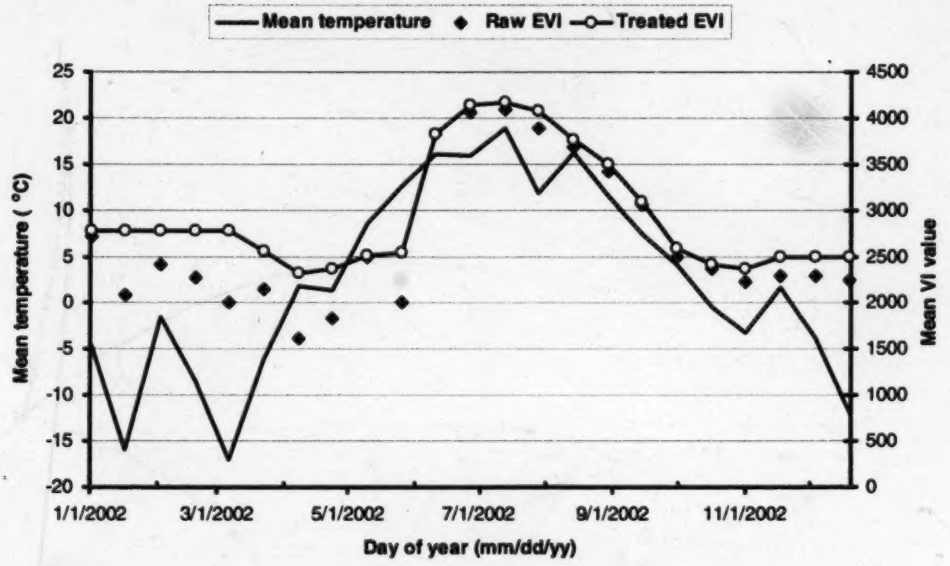

Figure C-9: Time series plot of mean temperature and EVI for the FORWARD study area in 2002.

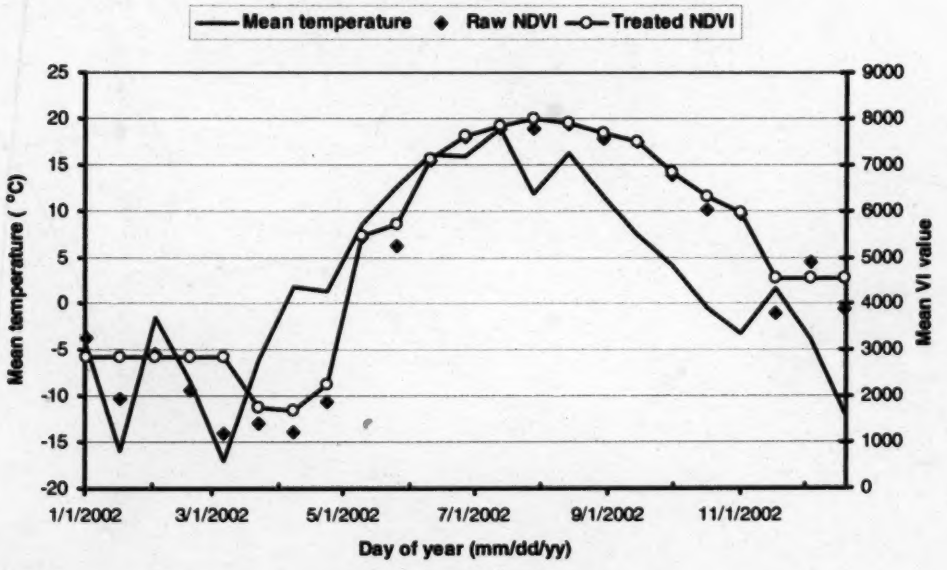

Figure 5-10: Time series plot of mean temperature and NDVI for the FORWARD study area in 2002.

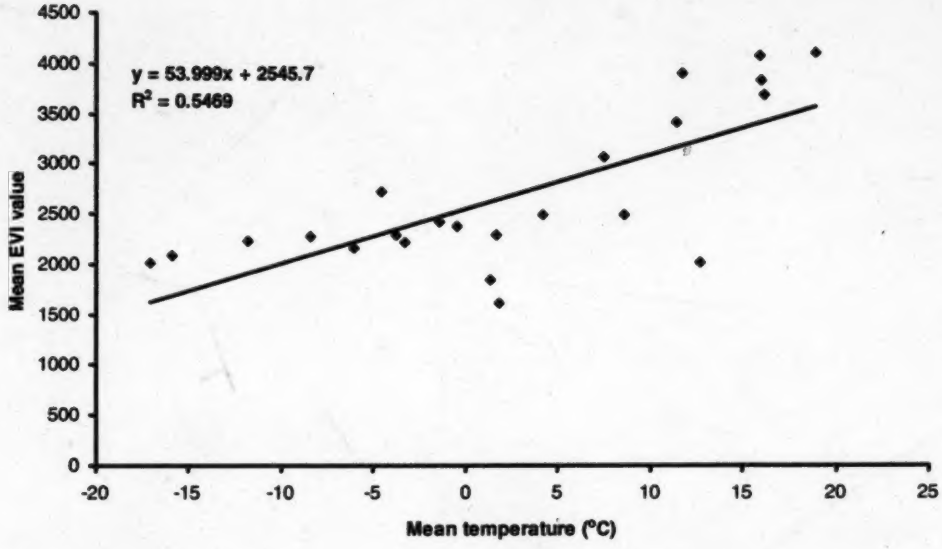

Figure C-11: Mean temperature versus mean EVI for the FORWARD study area in 2002.

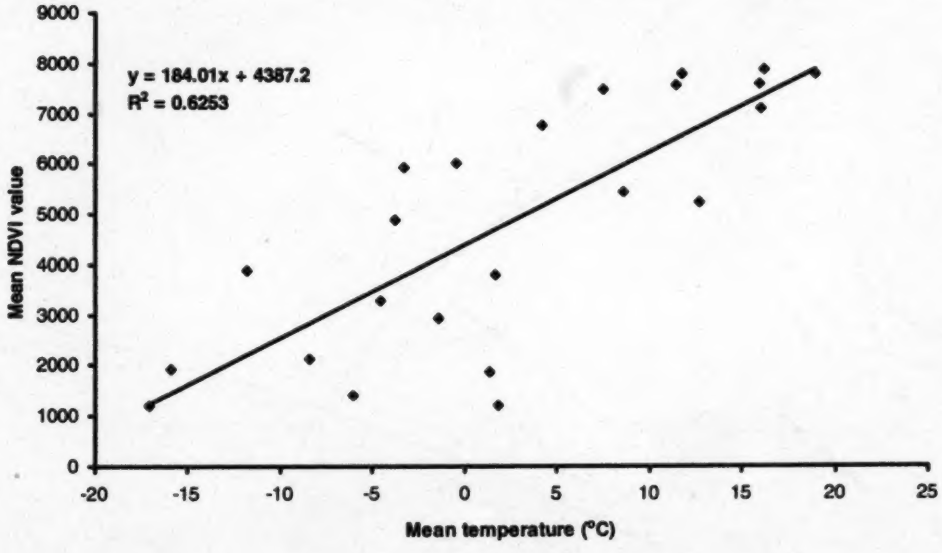

Figure C-12: Mean temperature versus mean NDVI for the FORWARD study area in 2002.

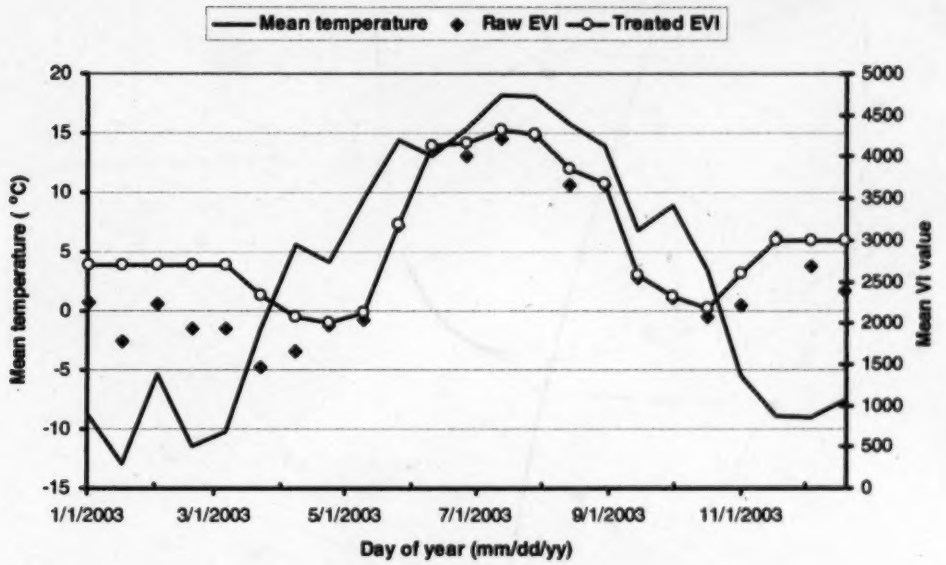

Figure C-13: Time series plot of mean temperature and EVI for the FORWARD study area in 2003.

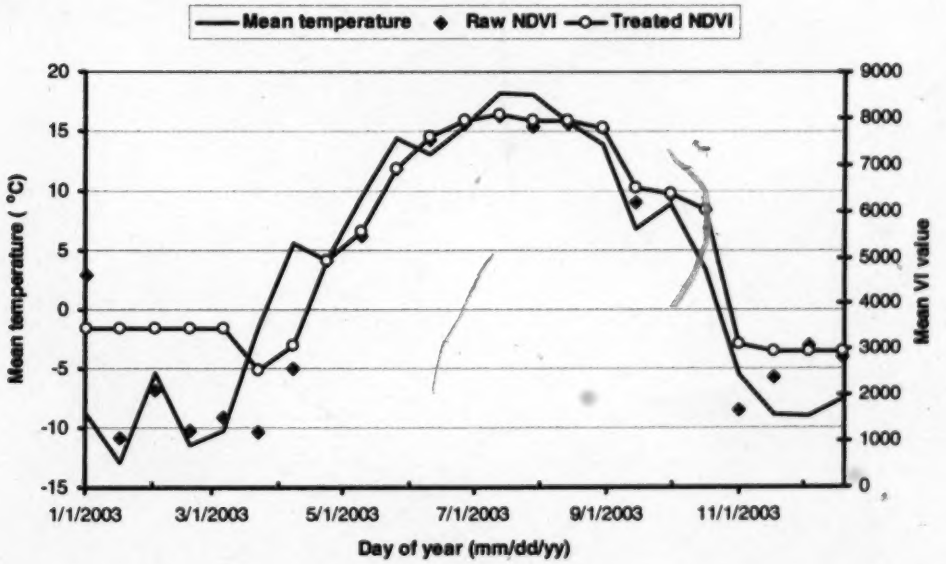

Figure C-14: Time series plot of mean temperature and NDVI for the FORWARD study area in 2003.

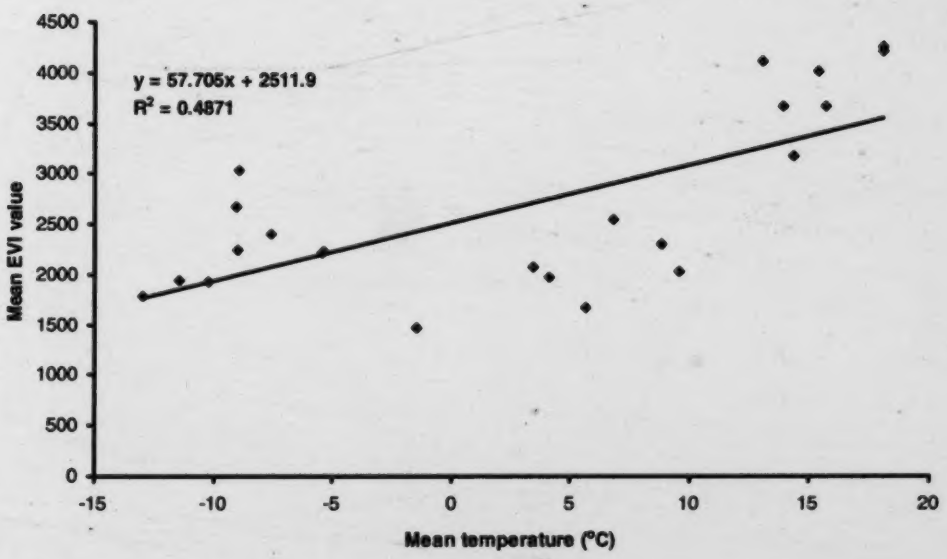

Figure C-15: Mean temperature versus mean EVI for the FORWARD study area in 2003.

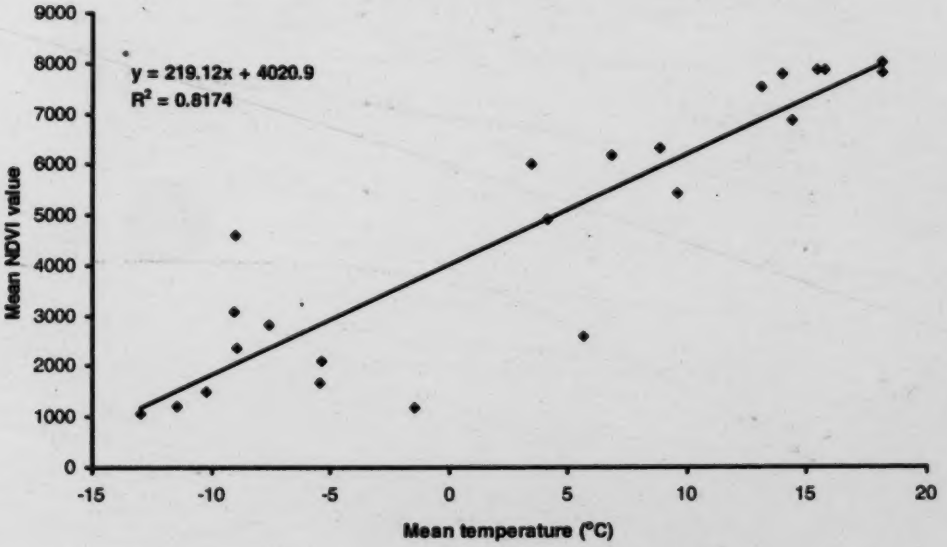

Figure C-16: Mean temperature versus mean NDVI for the FORWARD study area in 2003.

Table C-5: Difference between zeroes excluded and zeroes included mean EVIm VPMs for 2000-2003 for 16 watersheds.

Watersheds	Onset date	End date	Peak date	Onset value	End value	Peak value	Length	Time-int.VI	Rt of greenup	Rt of senescence
1A	0	2	27	0	28	738	2	4750	29	102
	11	9	51	266	95	1044	-3	9009	39	101
	6	6	36	162	71	966	0	7857	60	76
	12	12	42	246	145	1139	0	7638	164	115
Burnt pine	2	3	8	38	33	231	1	1768	24	23
	3	7	10	68	77	259	4	2178	28	25
	12	0	26	300	0	681	-12	5940	70	53
	1	18	16	15	198	489	17	3552	88	48
Cassidy	0	0	17	0	0	514	0	3703	7	48
	0	0	18	25	0	552	0	3395	49	78
	0	0	30	0	0	848	0	7674	6	73
	0	0	11	62	40	307	0	2258	27	35
Chickadee	0	0	25	55	66	649	0	4816	49	66
	0	0	32	106	87	903	0	6228	101	89
	0	0	44	289	86	1133	0	9136	104	99
	0	0	34	148	153	840	0	6331	77	98
Fireweed	0	0	80	638	598	1613	0	10305	215	217
	0	0	54	314	288	1263	0	8859	156	150
	0	0	73	824	399	1560	0	11867	224	158
	0	0	70	564	442	1526	0	10544	171	188
Goose	0	0	105	943	926	2144	0	14447	346	243
	0	0	75	572	535	1544	0	10847	190	182
	0	0	84	909	562	1823	0	12969	274	190
	0	0	74	755	601	1523	0	10847	185	195
Kashka	0	0	45	303	219	916	0	6934	86	87
	0	0	29	84	119	723	0	4851	110	80
	0	0	71	610	282	1646	0	11905	231	153
	0	0	63	209	444	1507	0	10385	243	160
Millions	0	0	19	0	0	469	0	3389	19	45
	0	0	47	0	92	1288	0	7446	113	138
	0	0	54	201	0	1451	0	11120	88	81
	0	0	48	285	82	1147	0	8493	85	86
Mosquito	0	0	18	173	100	521	0	3915	65	46
	0	0	17	109	0	519	0	3408	58	54
	0	0	27	236	178	766	0	6508	106	58
	0	0	22	128	83	534	0	3842	48	69
Pierre	0	0	50	200	298	1049	0	7445	106	133
	0	0	55	197	115	1188	0	8457	68	133
	0	0	86	562	78	1867	0	14828	111	154
	0	0	35	119	164	833	0	6179	66	111
Sak A	0	0	38	264	256	930	0	6856	111	102
	0	0	39	287	216	891	0	6745	91	93
	0	0	47	465	232	1180	0	9660	127	109
	0	0	41	348	300	1024	0	7389	141	108
Sak B	0	0	13	33	71	321	0	2584	28	36

	0	0	8	73	17	221	0	1604	40	22
	0	0	54	286	163	1321	0	10250	139	121
	0	0	42	66	445	1052	0	7751	97	139
Thistle	0	0	47	235	142	1151	0	8087	113	135
	0	0	73	441	336	1786	0	12423	188	199
	0	0	67	486	364	1674	0	13295	175	170
	0	0	79	529	255	1869	0	12950	242	211
Toby	0	0	16	86	143	391	0	2836	38	49
	0	0	32	203	168	844	0	5775	111	73
	0	0	53	301	41	1451	0	11583	74	142
	0	0	42	89	324	993	0	7391	84	127
Two creek	3	7	26	56	83	653	4	4719	46	80
	6	12	35	136	125	822	6	6280	60	80
	9	4	38	218	43	967	-5	7641	70	93
	6	10	26	125	111	677	4	4983	78	70
Willow	0	0	21	65	114	568	0	4213	63	56
	0	0	28	124	57	741	0	5469	83	75
	0	0	57	479	132	1643	0	13550	169	131
	0	0	45	254	204	1137	0	8395	110	152

Table C-6: Difference between zeroes excluded and zeroes included mean NDVIm VPMs for 2000-2003 for 16 watersheds.

Watersheds	Onset date	End date	Peak date	Onset value	End value	Peak value	Length	Time-int.VI	Rt of greenup	Rt of senescence
1A	0	0	12	0	0	430	0	4953	3	51
	2	0	31	107	0	1079	-2	12862	6	135
	0	0	24	0	0	861	0	9463	0	61
	0	0	2	0	0	72	0	818	0	5
Burnt pine	0	0	18	0	0	730	0	8243	0	59
	0	0	15	0	0	622	0	7701	3	49
	0	0	5	0	0	190	0	2042	0	11
	0	0	0	0	0	0	0	0	0	0
Cassidy	0	0	16	0	0	642	0	7406	0	60
	0	0	55	721	0	2127	0	23725	54	179
	0	0	7	0	0	253	0	2865	0	18
	0	0	0	0	0	0	0	0	0	0
Chickadee	0	0	20	35	4	715	0	7807	2	70
	0	0	21	62	0	854	0	9869	8	92
	0	0	10	18	0	340	0	3691	1	28
	0	0	1	16	4	35	0	393	0	3
Fireweed	0	0	6	0	0	200	0	1616	5	18
	0	0	30	0	0	1076	0	11562	0	105
	0	0	29	141	0	932	0	8789	25	76
	0	0	0	1128	59	0	0	0	0	0
Goose	0	0	15	47	53	472	0	4585	10	42
	0	0	19	48	13	636	0	6854	7	61
	0	0	23	602	21	751	0	7143	52	67

	0	0	3	839	104	105	0	1064	2	13
Kashka	0	0	21	0	0	721	0	7105	0	78
	0	0	37	112	0	1412	0	15825	15	244
	0	0	14	0	0	471	0	5243	0	53
	0	0	0	0	0	0	0	0	0	0
Millions	0	0	3	0	0	118	0	1576	0	13
	0	0	31	564	0	1402	0	17928	43	106
	0	0	7	0	0	235	0	2941	0	18
	0	0	0	0	0	0	0	0	0	0
Mosquito	0	0	6	133	0	205	0	2319	0	19
	0	0	5	187	0	205	0	2288	15	15
	0	0	5	0	0	201	0	2201	0	16
	0	0	0	35	0	0	0	0	0	0
Pierre	0	0	21	0	0	681	0	7794	5	72
	0	0	39	159	0	1319	0	15605	15	169
	0	0	27	0	0	950	0	9167	0	53
	0	0	0	0	0	0	0	0	0	0
Sak A	0	0	13	1	2	452	0	4946	1	42
	0	0	31	24	1	1120	0	13127	5	120
	0	0	17	229	1	600	0	6321	11	49
	0	0	2	347	41	66	0	719	0	6
Sak B	0	0	4	0	0	163	0	1731	0	13
	0	0	17	26	0	648	0	6789	5	80
	0	0	6	37	0	202	0	2075	0	23
	0	0	0	266	164	0	0	0	0	0
Thistle	0	0	10	120	19	360	0	4221	2	44
	0	0	32	51	0	1108	0	14155	0	155
	0	0	20	38	0	674	0	7390	0	66
	0	0	0	16	18	0	0	0	0	0
Toby	0	0	3	0	0	126	0	1457	0	9
	0	0	21	175	0	771	0	8919	19	93
	0	0	30	0	0	1118	0	10975	0	53
	0	0	0	0	0	0	0	0	0	0
Two creek	0	0	25	22	3	918	0	9729	2	98
	1	0	26	44	3	969	0	11912	4	120
	0	0	6	31	0	238	0	2532	3	18
	0	0	1	4	4	20	0	224	0	2
Willow	0	0	14	107	24	523	0	5566	3	48
	0	0	22	47	14	799	0	9358	6	88
	0	0	10	61	15	360	0	3781	3	30
	0	0	1	42	42	26	0	282	3	2

Table C-7*a*: Temporal average over 2000 to 2003 of the difference between zeroes excluded and zeroes included mean EVIm VPMs for 16 watersheds.

Onset date		End date		Peak date		Onset value		End value	
Cassidy	0	Cassidy	0	Burnt pine	15	Cassidy	22	Cassidy	10
Chickadee	0	Chickadee	0	Cassidy	19	Burnt pine	105	Millions	43
Fireweed	0	Fireweed	0	Mosquito	21	Sak B	115	Burnt pine	77
Goose	0	Goose	0	Sak B	29	Millions	122	1A	85
Kashka	0	Kashka	0	Two creek	31	Two creek	134	Mosquito	90
Millions	0	Millions	0	Chickadee	34	Chickadee	149	Two creek	91
Mosquito	0	Mosquito	0	Toby	36	Mosquito	161	Chickadee	98
Pierre	0	Pierre	0	Willow	38	1A	168	Willow	127
Sak A	0	Sak A	0	1A	39	Toby	170	Pierre	164
Sak B	0	Sak B	0	Sak A	41	Willow	230	Toby	169
Thistle	0	Thistle	0	Millions	42	Pierre	270	Sak B	174
Toby	0	Toby	0	Kashka	52	Kashka	302	Sak A	251
Willow	0	Willow	0	Pierre	57	Sak A	341	Kashka	266
Burnt pine	4	Burnt pine	7	Thistle	66	Thistle	423	Thistle	274
Two creek	6	1A	7	Fireweed	69	Fireweed	585	Fireweed	432
1A	7	Two creek	8	Goose	84	Goose	795	Goose	656

Table C-7*b*: Temporal average over 2000 to 2003 of the difference between zeroes excluded and zeroes included mean EVIm VPMs for 16 watersheds.

Peak value		Length		Time-int.VI		Rt of greenup		Rt of senescence	
Burnt pine	415	1A	0	Burnt pine	3359	Cassidy	22	Burnt pine	37
Cassidy	555	Cassidy	0	Cassidy	4258	Burnt pine	53	Mosquito	57
Mosquito	585	Chickadee	0	Mosquito	4418	Two creek	64	Cassidy	59
Sak B	729	Fireweed	0	Sak B	5547	Mosquito	69	Sak B	79
Two creek	780	Goose	0	Two creek	5906	1A	73	Two creek	81
Chickadee	881	Kashka	0	Chickadee	6628	Sak B	76	Millions	88
Toby	920	Millions	0	Toby	6896	Millions	76	Chickadee	88
1A	972	Mosquito	0	1A	7313	Toby	77	Toby	98
Sak A	1006	Pierre	0	Millions	7612	Chickadee	83	1A	98
Willow	1022	Sak A	0	Sak A	7662	Pierre	88	Sak A	103
Millions	1089	Sak B	0	Willow	7907	Willow	106	Willow	104
Kashka	1198	Thistle	0	Kashka	8519	Sak A	117	Kashka	120
Pierre	1234	Toby	0	Pierre	9227	Kashka	168	Pierre	133
Fireweed	1491	Willow	0	Fireweed	10394	Thistle	180	Fireweed	178
Thistle	1620	Two creek	2	Thistle	11689	Fireweed	191	Thistle	179
Goose	1759	Burnt pine	3	Goose	12278	Goose	249	Goose	202

Table C-8*a*: Temporal average over 2000 to 2003 of the difference between zeroes excluded and zeroes included mean NDVIm VPMs for 16 watersheds.

Onset date		End date		Peak date		Onset value		End value	
1A	0	1A	0	Mosquito	4	Burnt pine	0	1A	0
Burnt pine	0	Burnt pine	0	Sak B	7	Two creek	25	Burnt pine	0
Cassidy	0	Cassidy	0	Burnt pine	10	1A	27	Cassidy	0
Chickadee	0	Chickadee	0	Millions	10	Kashka	28	Kashka	0
Fireweed	0	Fireweed	0	Willow	11	Chickadee	33	Millions	0
Goose	0	Goose	0	Chickadee	13	Pierre	40	Mosquito	0
Kashka	0	Kashka	0	Toby	13	Toby	44	Pierre	0
Millions	0	Millions	0	Two creek	15	Thistle	56	Toby	0
Mosquito	0	Mosquito	0	Goose	15	Willow	64	Chickadee	2
Pierre	0	Pierre	0	Sak A	16	Sak B	82	Two creek	3
Sak A	0	Sak A	0	Thistle	16	Mosquito	89	Thistle	9
Sak B	0	Sak B	0	Fireweed	16	Millions	141	Sak A	11
Thistle	0	Thistle	0	1A	17	Sak A	150	Fireweed	15
Toby	0	Toby	0	Kashka	18	Cassidy	180	Willow	24
Two creek	0	Two creek	0	Cassidy	19	Fireweed	317	Sak B	41
Willow	0	Willow	0	Pierre	22	Goose	384	Goose	48

Table C-8*b*: Temporal average over 2000 to 2003 of the difference between zeroes excluded and zeroes included mean NDVIm VPMs for 16 watersheds.

Peak value		Length		Time-int.VI		Rt of greenup		Rt of senescence	
Mosquito	153	1A	0	Mosquito	1702	Thistle	1	Mosquito	12
Sak B	253	Burnt pine	0	Sak B	2649	Burnt pine	1	Sak B	29
Burnt pine	385	Cassidy	0	Burnt pine	4496	Sak B	1	Burnt pine	30
Willow	427	Chickadee	0	Willow	4747	Two creek	2	Millions	34
Millions	439	Fireweed	0	Goose	4912	1A	2	Toby	39
Chickadee	486	Goose	0	Toby	5338	Chickadee	3	Willow	42
Goose	491	Kashka	0	Chickadee	5440	Kashka	4	Goose	46
Toby	504	Millions	0	Fireweed	5492	Mosquito	4	Chickadee	48
Thistle	536	Mosquito	0	Millions	5611	Willow	4	Fireweed	50
Two creek	536	Pierre	0	Two creek	6099	Sak A	4	Sak A	54
Fireweed	552	Sak A	0	Sak A	6278	Toby	5	Two creek	60
Sak A	560	Sak B	0	Thistle	6442	Pierre	5	1A	63
1A	611	Thistle	0	1A	7024	Fireweed	8	Cassidy	64
Kashka	651	Toby	0	Kashka	7043	Millions	11	Thistle	66
Pierre	738	Two creek	0	Pierre	8141	Cassidy	13	Pierre	74
Cassidy	755	Willow	0	Cassidy	8499	Goose	18	Kashka	94